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FLAT GLASS MANUFACTURING PLANTS

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16. ABSTRACT The report describes air pollutants emitted during the production of flat glass, SIC No. 3211. It covers raw materials preparation at the plant site, molten glass production in the melting furnace, and the forming of flat glass products. Melting furnace emissions account for over 99% of the total plant emissions; NOx, SOx, and particulates are the major (>99%) pollutants. The particulates are alkali sulfates of submicron size. NOx has the highest emission factor (4 g/kg) and annual emissions (16,000 metric tons). When national emissions of each pollutant from this industry are compared to the corresponding national emissions from all stationary sources, NOx contributes 0.07% of the total. Source severity is a measure of the potential environmental effect of air emissions from this industry: it is defined as the ratio of the maximum average ground level concentration compared to the primary ambient air quality standard for criteria pollutants. The largest severity factors are for NOx emissions from a 30 m stack (S=1.3) and a 60 m stack (S=0.57). Severities for SOx and particulates are in the range 1.0-0.05.

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PREFACE

The Industrial Environmental Research Laboratory (IERL) of EPA has the responsibility for insuring that air pollution control technology is available for stationary sources. If control technology is unavailable, inadequate, uneconomical or socially unacceptable, then development of the needed control techniques is conducted by IERL. Approaches considered include: process modifications, feedstock modifications, add on control devices, and complete process substitution. The scale of control technology programs range from bench to full scale demonstration plants.

The Chemical Processes Branch of IERL has the responsibility for developing control technology for a large number (>500) of operations in the chemical and related industries. As in any technical program the first step is to identify the unsolved problems.

Each of the industries is to be examined in detail to determine if there is sufficient potential environmental risk to justify the development of control technology by IERL. This report contains the data necessary to make that decision for flat glass manufacturing plants.

Monsanto Research Corporation has contracted with EPA to investigate the environmental impact of various industries which represent sources of emissions in accordance with EPA's responsibility as outlined above. Dr. Robert C. Binning serves as Program Manager in this overall program entitled, "Source Assessment," which includes the investigation of sources in each of four categories: combustion, organic materials, inorganic materials and open sources. In this study of flat glass manufacturing plants, Mr. Edward J. Wooldridge served as EPA Project Leader.

This study was completed by IERL-RTP. Project responsibility was transferred to the Industrial Pollution Control Division of IERL-Cincinnati on October 15, 1975.

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LIST OF SYMBOLS

Symbol	Definition
AAQS	Ambient air quality standard
A, B, C, D, E, F	Atmospheric stability classes
a, b, c, d, e, f	Constants in dispersion equations
A_R	The ratio $Q/ac\pi u$
B_R	The ratio $-H^2/2c^2$
D_i	Inside stack diameter
e	Natural logarithm base
H	Effective stack height
h	Physical stack height
ΔH	Plume rise
k	"Student t" test variable
n	Number of samples
p	Atmospheric pressure
Q	Mass emission rate
s	Sample standard deviation
S	Source severity, ratio $\overline{\chi}_{max}$/AAQS
T_a	Ambient temperature
T_s	Stack gas temperature
t_0	Instantaneous averaging time of 3 minutes
t	Averaging time
TLV	Threshold limit value
u	National average wind speed
V_s	Stack gas exit velocity
x	Downwind dispersion distance from source of emission release

LIST OF SYMBOLS (Continued)

Symbol	Definition
y	Horizontal distance from centerline of dispersion
$\overline{y}$	Sample mean
π	3.14
σ_y	Standard deviation of horizontal dispersion
σ_z	Standard deviation of vertical dispersion
χ	Downwind ground level concentration at reference coordinate x and y with emission height of H
$\overline{\chi}$	Time average ground level concentration of an emission
χ_{max}	Instantaneous maximum ground level concentration
$\overline{\chi}_{max}$	Time average maximum ground level concentration

SECTION I

INTRODUCTION

Flat glass is manufactured at 29 plants in 14 states, and the production of finished products amounted to 2.9 x 10^6 metric tons[a] in 1972. However, total production was approximately 4 x 10^6 metric tons, the difference being lost to breakage, edge loss, cutting, and off-quality glass.

This report discusses air emissions released during the manufacture of flat glass. The different emission points within the manufacturing process are identified, the types and quantities of emissions from each point are delineated, and the characteristics of air pollutants are listed. State and national emissions of criteria pollutants (particulates, NO_x, SO_x, CO, and hydrocarbons) from the flat glass industry are compared to total state and national emissions from all stationary sources. The maximum average ground level concentrations of emissions from a typical flat glass plant are compared to the corresponding ambient air quality standards. The effect of present and emerging control technology is also discussed.

The manufacturing process is divided into three phases: (1) preparation of raw materials, (2) glass melting, and

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[a] 1 metric ton = 10 grams = 2,205 pounds - 1.1 short tons (short tons are designated "tons" in this document); other conversion factors and metric system prefixes are presented in Section X.

(3) forming and finishing operations. The first two operations are common to all flat glass products while the latter has four variations:

- Manufacture of float glass (77% of total capacity).
- Manufacture of sheet glass (17% of total capacity).
- Manufacture of rolled glass (4% of total capacity).
- Manufacture of plate glass (2% of total capacity).

During the past 10 years, the float process has replaced almost all of the older plate glass capacity, and only one plate glass plant is still in operation. The future may see a changeover of some sheet glass production to thin float glass.

SECTION II

SUMMARY

This document describes a study of air emissions released during the production of flat glass, Standard Industrial Classification No. 3211. It encompasses the preparation of raw materials (sand, limestone, and soda ash) at the plant site, the production of molten glass in the melting furnace, and the forming of flat glass products (sheet glass, float glass, and rolled glass). It does not cover the production of plate glass, which is now practiced commercially at only one plant in the United States.

The estimated 1972 production of finished flat glass products was 2.9×10^6 metric tons (3.2 million tons) ± 10%. The amount of glass actually made was higher ($\sim 4 \times 10^6$ metric tons) because of breakage and off-quality glass. The quantity of raw materials handled was 4.5×10^6 metric tons, of which 5×10^5 metric tons volatilized (over 90% to CO_2) during melting.

Flat glass is manufactured at 29 plants in 14 states, with Tennessee, Pennsylvania, and Ohio accounting for 46% of total capacity. The average county population density at a plant site is 248 persons/km^2. The majority of flat glass capacity is float glass (77%) while sheet glass accounts for 17%, rolled glass for 4%, and plate glass for 2% of the total.

A typical flat glass plant has a capacity of 500 metric tons/day (550 tons/day) and a yearly production (75% capacity) of 1.4×10^5 metric tons. Over 99% of the plant emissions arise from the glass melting furnace, with NO_x, SO_x, and particulates the major (>99%) pollutants. The particulates are alkali sulfates of submicron particle size. Furnace stack heights average 30 m (100 ft) when ejection air is used and 60 m (200 ft) for natural draft.

Emissions from the melting furnace are listed in Table 1 along with emission factors and total annual emissions. Nitrogen oxides have the highest emission factor (4 g/kg) and annual emissions (1.6×10^4 metric tons). When national emissions of each pollutant from the flat glass industry are compared to the corresponding national emissions from all stationary sources, NO_x also contributes the greatest percent (0.07%). The greatest contributions on a statewide basis are for NO_x emissions in Tennessee (0.6%) and Oklahoma (0.5%).

Table 1. EMISSIONS FROM THE GLASS MELTING FURNACE

Species	Emission factor, g/kg (lb/ton)	Total annual emissions (based on 4.0×10^6 metric tons glass manufactured), 10^3 metric tons (tons)	Percent of national emissions from all stationary sources
NO_x	4 ± 30% (8)	16.0 ± 4.8 (17,600)	0.07
SO_x	1.5 ± 27% (3)	6.0 ± 1.6 (6,600)	0.02
Particulates	1 ± 60% (2)	4.0 ± 2.4 (4,400)	0.02
CO	0.02 ± 100% (0.04)	0.08 ± 0.08 (88)	<0.01
Hydrocarbons	0.04 ± 100% (0.08)	0.16 ± 0.16 (180)	<0.01

The preparation of raw materials gives rise to particulate emissions (90 metric tons/yr ± 100%) from handling operations (unloading, conveying, storage bin vents, glass crushers, and raw material mixers. The composition of the emissions is the same as that of the raw materials (i.e., sand, soda ash, lime). Dusting is controlled by enclosing the handling operations and filtering the exhaust air from storage bins, crushers, and mixers. In addition, the glass batch ingredients are purchased with size specifications that limit the amount of <44 μm (<325-mesh) particles. Over 90% of the industry employs controls, and the average emission factor for this phase of production is 0.02 g/kg (0.04 lb/ton) ± 100% of material processed.

The only atmospheric emissions from forming and finishing operations are combustion products from gas-fired annealing lehrs. The amount of these emissions is so small (national emissions <100 metric tons/yr) that they are not controlled.

Emissions from flat glass melting furnaces are not controlled with add-on equipment because the industry is able to meet emission standards with proper operating conditions. Submicron particulates in the stack gas may cause opacity limits to be exceeded. These emissions have been controlled in other sectors of the glass industry by baghouses and electrostatic precipitators. Although scrubbers were found to control SO_x emissions, operational problems were experienced and performance on particulates (<90% efficiency) was not satisfactory. No controls have been developed for NO_x emissions.

One measure of the potential environmental effect of melting furnace emissions is their maximum average ground level concentrations ($\overline{\chi}_{max}$). These have been calculated for a typical flat glass (500 metric tons/day) plant and appear in Table 2. A Gaussian plume dispersion model was used to calculate values of $\overline{\chi}_{max}$ for stack heights of 30 m and 60 m.

Table 2. SOURCE SEVERITY FOR FLAT GLASS EMISSIONS

Emission	Primary ambient air quality standard, mg/m^3	Primary ambient air quality standard, Averaging time	$\overline{\chi}_{max}$, µg/m^3 Stack height =30m[a]	$\overline{\chi}_{max}$, µg/m^3 Stack height =60m[a]	S Stack height =30m[a]	S Stack height =60m[a]
NO_x	0.100	Annual arithmetic mean	130	57	1.3	0.57
SO_x	0.365	24 hr; not to be exceeded more than once per year	44	20	0.12	0.05
Particulates	0.260	24 hr; not to be exceeded more than once per year	29	13	0.11	0.05
CO	40.0	1 hr; not to be exceeded more than once per year	1.0	0.45	<0.01	<0.01
Hydrocarbons	0.160	3 hr; 6-9 AM	1.7	0.74	0.01	<0.01

[a] Effective stack height is 30 m higher due to plume rise.

The source severity, S, has been defined as the ratio of $\overline{\chi}_{max}$ to the primary ambient air quality standard (AAQS) for criteria pollutants. Values for S and AAQS are also listed in Table 2. The largest severity factors are for NO_x emissions from a 30 m stack (S = 1.3) and a 60 m stack (S = 0.57). The severities for SO_x and particulates lie between 1.0 and 0.05, while those for CO and hydrocarbons are ≤ 0.01.

The affected population has been defined as the population around a typical plant who are exposed to a $\overline{\chi}$ (average ground level concentration) value which is >0.1 or 1.0 of the corresponding AAQS. This value is given for each emission species in Table 3. The largest value is for NO_x emissions from a 30 m stack (14,600 persons).

Table 3. AFFECTED POPULATION

Emission	$\overline{\chi}$/AAQS > 0.1			
	Affected area, km^2		Affected population[a]	
	Stack height = 30 m[b]	Stack height = 60 m[b]	Stack height = 30 m[b]	Stack height = 60 m[b]
NO_x	59.0	55.8	14,600	13,800
SO_x	3.0	0	750	0
Particulates	2.6	0	640	0
CO	0	0	0	0
Hydrocarbons	0	0	0	0
	$\overline{\chi}$/AAQS > 1.0			
NO_x	2.8	0	703	0
SO_x	0	0	0	0
Particulates	0	0	0	0
CO	0	0	0	0
Hydrocarbons	0	0	0	0

[a] Based on an average population density of 248 persons/km^2.

[b] Effective stack height is 30 m higher due to plume rise.

Over the past 10 years the flat glass industry has experienced a profound technological change as the old plate glass manufacturing process has been replaced by the new float process. In the future float glass may also supplant much of the sheet glass market.

Flat glass production experienced an annual growth rate of 10% from 1967 to 1973. If growth recovers after the 1974 economic slump, 1978 production will be 46% above that of 1973. Industry emissions will also increase by this amount without new developments in control technology. Two factors which cannot be evaluated are the decrease in emissions due to better furnace operations, and the increase in emissions due to a conversion from gas to oil firing. Gas firing is preferred whenever possible because it causes less wear on refractories in the melting furnace.

SECTION III

DESCRIPTION OF THE FLAT GLASS INDUSTRY

A. TYPES OF GLASS PLANTS

The manufacture of glass is an important American industry with 1972 sales of $5.5 billion and glass production of 1.86×10^7 metric tons. The industry has been subdivided by the U.S. Department of Commerce into four categories[1] (Table 4), of which only flat glass is considered in this report. Manufacturing data in each group are compiled by the department and published in various government reports, the most comprehensive being the 1972 Census of Manufactures.[2-5]

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[1] Standard Industrial Classification Manual, 1972 Edition. Washington. Superintendent of Documents, 1972. p. 136-138.

[2] Preliminary Report, 1972 Census of Manufactures, Industry Series, Flat Glass, SIC 3211. U.S. Department of Commerce. Washington. MC 72(P)-32A-1. January 1974. 7 p.

[3] Preliminary Report, 1972 Census of Manufactures, Industry Series, Glass Containers, SIC 3221. U.S. Department of Commerce. Washington. MC 72(P)-32A-2. December 1973. 6 p.

[4] Preliminary Report, 1972 Census of Manufactures, Industry Series, Pressed and Blown Glass, SIC 3229. U.S. Department of Commerce. Washington. MC 72(P)-32A-3. February 1974. 7 p.

[5] Preliminary Report, 1972 Census of Manufactures, Industry Series, Products of Purchased Glass, SIC 3231. U.S. Department of Commerce. Washington. MC 72(P)-32A-4. February 1974. 7 p.

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Table 4. U.S. GLASS INDUSTRY, 1972[2-5]

Standard Industrial Classification (SIC)	Production of glass, 10^6 metric tons (details in Appendix A)	Percent of total production	Number of plants
3211 - Flat glass	2.9	15.6	31[b]
3221 - Glass containers	11.7	62.9	115
3229 - Pressed and blown glass, N.E.C. (not elsewhere classified)	4.0	21.5	254
3231 - Products of purchased glass	0[a]	0	860
TOTAL	18.6	100.0	1,260

[a] Plants in this industry use glass made at other sites.

[b] Two plants have closed since 1972.

The flat glass industry is composed of 29 plants in 14 states. These are listed by company in Table 5, along with the type of glass they produce: float glass, plate glass, sheet glass, or rolled glass.[6,7]

The four flat glass products differ in the way they are formed. Float glass is made by floating molten glass from the melting furnace on a bath of molten tin until the glass hardens. This glass, with its high optical quality, has replaced the old plate glass which required grinding and

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[6] Directory Issue. The Glass Industry. 54(10):1-178, September 1973.

[7] 1974 Glass Factory Directory Issue. American Glass Review. 94(8A):1-204, February 1974.

Table 5. PLANT LISTING FOR FLAT GLASS INDUSTRY[6,7]
(A more detailed listing is given in Appendix B.)

Company and location	Type and estimated plant capacity,[a] metric tons/day			
	Float	Plate	Sheet	Rolled
PPG Industries				
Carlisle, PA	900			
Cumberland, MD	400			
Crystal City, MO	360			
Fresno, CA			360	
Meadville, PA	730			
Mt. Vernon, OH			600	
Mt. Zion, IL			360	
Wichita Falls, TX	900			
Total est. capacity	3,290		1,320	
Libbey-Owens-Ford Co.				
Charleston, WV			360	
Lathrop, CA	400			
Laurinburg, NC	680			
Ottawa, IL	360			
Rossford, OH	900			
Toledo, OH	400			
Total est. capacity	2,740		360	
Ford Motor Co., Glass Div.				
Dearborn, MI	360			
Nashville, TN	1,360			
Tulsa, OK	900			
Total est. capacity	2,620			
ASG Industries, Inc.				
Greenland, TN	400	320		
Jeanette, PA			245	
Kingsport, TN				295
Okmulgee, OK			160	
Total est. capacity	400	320	405	295

[a] Data on plant capacities were estimated based on communication with flat glass manufacturers; data on ASG, Fourco and CE Glass are contained in References 6 and 7.

Table 5 (continued). PLANT LISTING FOR FLAT GLASS INDUSTRY

Company and location	Type and estimated plant capacity,[a] metric tons/day Float	Plate	Sheet	Rolled
CE Glass, Inc.				
Cinnaminson, NJ	450			
Erwin, TN				64
Floreffe, PA	360			
Fullerton, CA				64
St. Louis, MO				177
Total est. capacity	810			305
Fourco Glass Co.				
Clarksburg, WV			180	
Fort Smith, AR			200	
Total est. capacity			380	
Guardian Industries				
Carleton, MI	820			
Total est. capacity	820			
TOTAL VALUES				
Capacity, metric tons	10,680	320	2,460	600
Percentage	77	2	17	4
Number of plants	17	1	8	4
Number of melting furnaces	25	1	14	9

TOTAL CAPACITY	14,060 metric tons/day
Average plant capacity:	500 metric tons/day
Average float plant capacity:	600 metric tons/day
Average sheet plant capacity:	300 metric tons/day
Average rolled plant capacity:	150 metric tons/day

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[a] Data on plant capacities were estimated based on communications with flat glass manufacturers; data on ASG, Fourco and CE Glass are contained in References 6 and 7.

polishing to produce a smooth surface. It is used for automobile windows and large picture windows. Average thicknesses range from 3.2 mm to 6.4 mm.

Sheet glass is made by drawing molten glass upward from the melt. It is thinner than float glass (1.6 mm to 3.2 mm) and is used for windows in residential construction.

Rolled or patterned glass is formed by drawing molten glass through rollers with patterns impressed on them. This decorative glass is used for special purposes such as shower doors and partitions.

Plate glass is made by drawing molten glass through smooth rollers, and then grinding and polishing both glass surfaces to a smooth finish. Only one plate glass furnace is still in operation in the U.S.

Table 5 also lists the capacity of all 29 flat glass plants, and gives total capacities for each flat glass product. Average plant capacity is 500 metric tons/day. The product breakdown is: float glass, 77%; plate glass, 2%; sheet glass, 17%; and rolled glass, 4%.

The distribution of plants across the country is shown in Figure 1. A detailed listing by state, county and Air Quality Control Region (AQCR) appears in Appendix B. The average county population density of the counties containing plants is 248 persons/km^2.

B. TYPES OF GLASS

Glass is normally defined as an inorganic product of fusion which has cooled to a rigid condition without crystallizing. The chemical composition and corresponding properties may

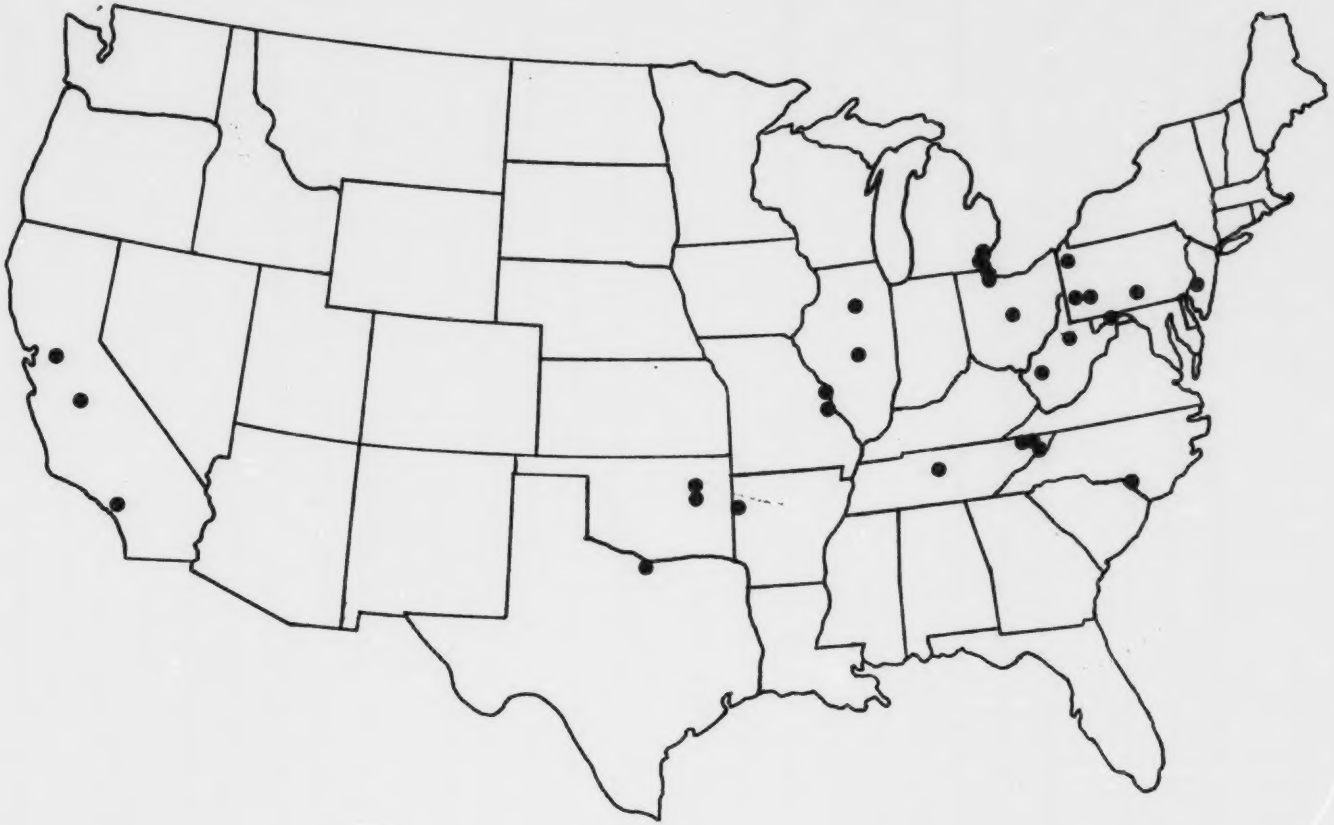

Figure 1. Locations of flat glass plants

vary over a wide range. Over 90% of the glass made, and 100% of the flat glass produced, is called soda-lime glass. The name is derived from its basic ingredients of sand (SiO_2), soda ash (Na_2CO_3), and limestone (basically $CaCO_3$ plus some $MgCO_3$). Other types of glass used for special purposes are borosilicate glass (heat resistance), lead glass (crystal artware, TV tubes) and opal glass (tableware). The compositions of these commercial glasses are given in Table 6.[8-10]

Glass raw materials, indigenous to many parts of the country, are inexpensive. Glass sand is the source of SiO_2 and it should be of high purity (>99% SiO_2). The impurities in glass sand are Al_2O_3 and Fe_2O_3. Although iron is an objectionable impurity in other types of glass because of its greenish tinge, it is often added in small amounts (0.1%) to flat glass (e.g., automobile window glass).

Soda ash is 98% to 100% Na_2CO_3, with NaCl as the major impurity in soda ash made by the Solvay process.[9,10] Naturally derived soda ash contains ~0.025% NaCl.

Limestone is available as high-calcium limestone consisting essentially of calcite, $CaCO_3$ (95%), and dolomitic limestone which is a mixture of dolomite ($CaCO_3 \cdot MgCO_3$) and calcite.

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[8] Dietz, E. D. Glass. In: Chemical and Process Technology Encyclopedia, Considine, D. M. (ed.). New York, McGraw-Hill Book Co., 1974. p. 552-561.

[9] Hutchins, J. R., and R. V. Harrington. Glass. In: Kirk-Othmer Encyclopedia of Chemical Technology, 2nd Edition, Vol. 10, Standen, A. (ed.). New York, Interscience Publishers, Divn. of John Wiley & Sons, Inc., 1966. p. 533-604.

[10] Shreve, R. N. Chemical Process Industries, 3rd Edition. New York, McGraw-Hill Book Co., 1967. p. 190-210

Table 6. COMPOSITIONS BY WEIGHT PERCENT OF COMMERCIAL GLASSES[8-10]

Component	Soda-lime glasses			Borosilicate glass[a]	Lead glass[a]
	Containers	Flat glass	Tableware		
SiO_2	70 to 74	71 to 74	71 to 74	70 to 82	35 to 70
Al_2O_3	1.5 to 2.5	0 to 2	0.5 to 2	2 to 7.5	0.5 to 2.0
B_2O_3	0	0	0	9 to 14	0
Na_2O	13 to 16	12 to 15	13 to 15	3 to 8	4 to 8
K_2O					5 to 10
CaO	10 to 14	8 to 12	5.5 to 7.5	0.1 to 1.2	0
MgO			4.0 to 6.5		
BaO	0	0	0	0 to 2.5	0
PbO	0	0	0	0	12 to 60

[a] Specialty glassware.

Quality limestones contain less than 0.1% Fe_2O_3 and about 1% silica and alumina.[9]

Cullet, which is scrap glass that is to be recycled, makes up from 30% to 50% of the total charge to a flat glass melting furnace.[a] Use of cullet facilitates higher melting rates and utilizes a waste material.[9,10]

In addition to these major ingredients, feldspar ($R_2O \cdot Al_2O_3 \cdot 6SiO_2$ where R = Na or K) is added to sheet glass as a source of aluminum, while salt cake (Na_2SO_4) is added as a fluxing agent. Fluxes promote the melting process by reacting with silica to form lower melting silicates. A typical glass batch recipe is:[11]

Silica sand	910 kg	(55.6%)
Soda ash	302 kg	(18.5%)
Feldspar[b]	80 kg	(4.9%)
Limestone	309 kg	(18.9%)
Salt cake (Na_2SO_4)	36 kg	(2.1%)
TOTAL	1637 kg	(100.0%)

These ingredients melt down to 1,341 kg of glass and give off 295 kg of gases, primarily (>90%) CO_2. The batch volume of 1.27 m^3 produces 0.57 m^3 of fluid glass and 708 m^3 of gaseous products (measured at the furnace temperature of 1,500°C).[11]

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[a] Based on information from two flat glass manufacturers.

[b] Sheet glass only; not used in float glass.

[11] Holscher, H. H. The Glass Primer. New York, Magazines for Industry, Inc., 1972. 58 p.

Although many minor ingredients (<5% of the batch) can be added to the glass batch, very few are used in making flat glass. The only other ingredients used in making clear float glass are carbon in the form of powdered coal (used as a reducing agent for sulfates) and iron oxide (to provide a greenish tint). No borates, fluorides, selenium, or arsenic compounds are added.[a] A small amount (<10% of total production) of colored float glass is made, but this has not been considered in this document.

The only major variation in the production of other types of flat glass is that iron oxide is not added. One sheet glass manufacturer still employs arsenic as a fining agent.[a] Fining is the process of removing gas bubbles from the melted glass. Fining agents react chemically in the melt and release gases that cause existing bubbles to increase in size and rise to the surface.[9] However, over half of all sheet glass (and at least 90% of all flat glass) is made without the use of arsenic,[a] and emissions of arsenic have not been studied for this report. The only compound that could be considered to act as a fining agent, that is still used in flat glass production, is sodium sulfate.

C. THE GLASS MANUFACTURING PROCESS

The manufacture of flat glass can be broken down into three basic steps:

- Preparation and handling of raw materials (includes mixing)
- Glass melting and refining
- Forming and finishing operations (includes annealing)

---

[a] Information supplied by two flat glass manufacturers.

A flow diagram of the overall process is shown in Figure 2.

1. Preparation of Raw Materials

A typical plant (500 metric tons/day) manufacturing float glass houses the raw material mixing and conveying equipment in a structure termed a "batch plant." Figure 3 is a flow diagram of a typical batch plant. The storage bins for major raw materials are elevated with the weigh hoppers and mixers located below them to make use of gravity flow.

Sand, soda ash, lime, and cullet (broken scrap glass) are conveyed from railroad hopper cars or hopper trucks by a combination of screw conveyors, belt conveyors, and bucket elevators, or by pneumatic conveyors to the elevated storage bins. Cullet from within the plant travels by belt conveyors to the cullet bin. Powdered coal and iron oxide are stored in small bins.

Ingredients comprising a batch of glass are dropped by gravity from the storage bins into weigh hoppers and then released to fall into the mixer. Cullet is ground and then mixed with the dry ingredients in the mixer. Ground cullet may also bypass the mixer and be mixed instead with the other blended materials in the bottom of a bucket elevator; unground cullet may be fed directly to the furnace.

Raw materials are blended in large (4 metric tons capacity) mixers. After 3 to 5 minutes, the mix is conveyed to a charge bin located alongside the melting furnace. At the bottom of the charge bins, rotary valves feed the blended materials into reciprocating- or screw-type furnace feeders which force the blended raw materials into one end of the glass melting furnace.

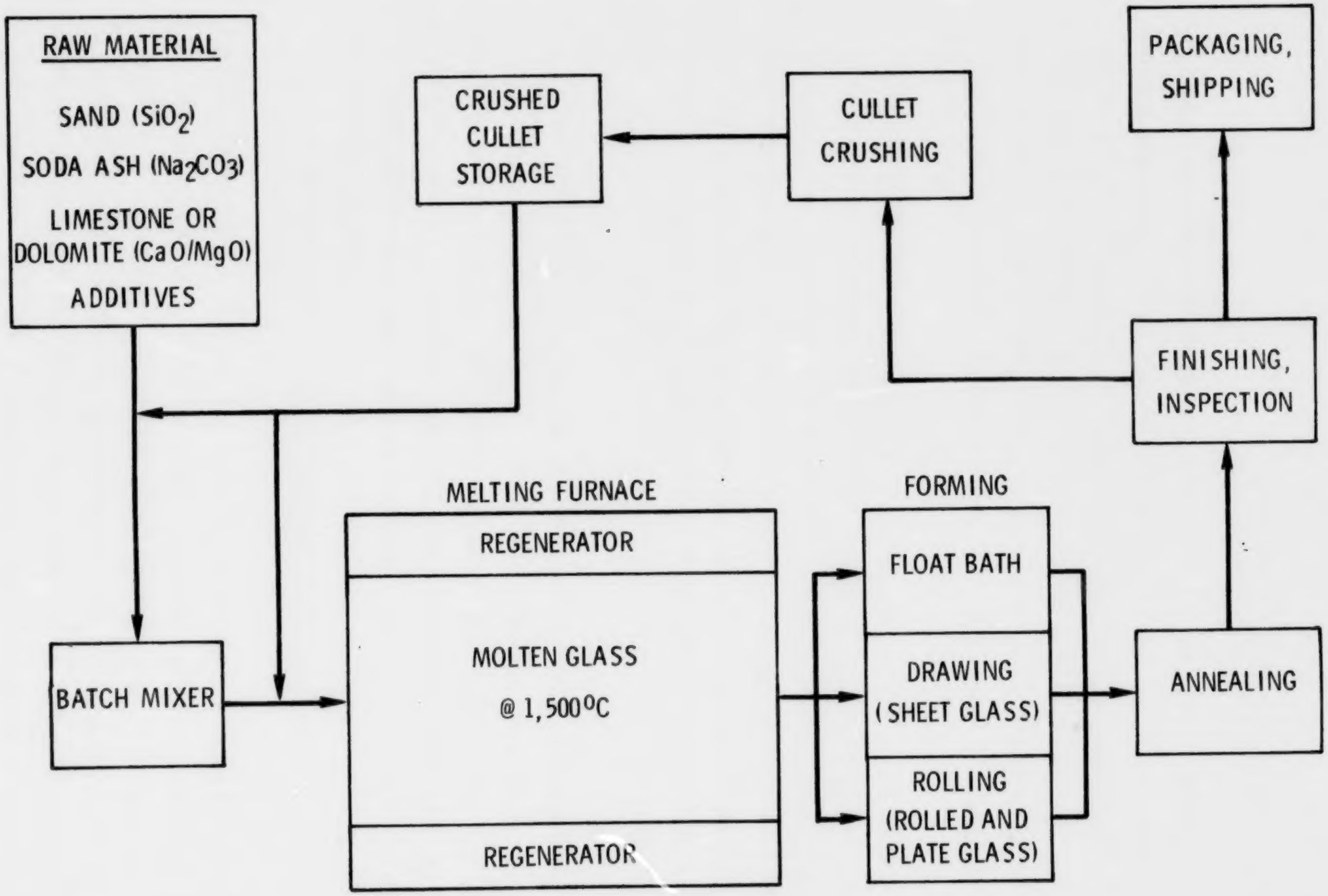
RAW MATERIAL
SAND (SiO_2)
SODA ASH (Na_2CO_3)
LIMESTONE OR
DOLOMITE (CaO/MgO)
ADDITIVES
CRUSHED CULLET STORAGE
CULLET CRUSHING
PACKAGING, SHIPPING
FINISHING, INSPECTION
BATCH MIXER
MELTING FURNACE
REGENERATOR
MOLTEN GLASS
@ 1,500°C
REGENERATOR
FORMING
FLOAT BATH
DRAWING (SHEET GLASS)
ROLLING (ROLLED AND PLATE GLASS)
ANNEALING

Figure 2. Flow diagram of flat glass manufacturing

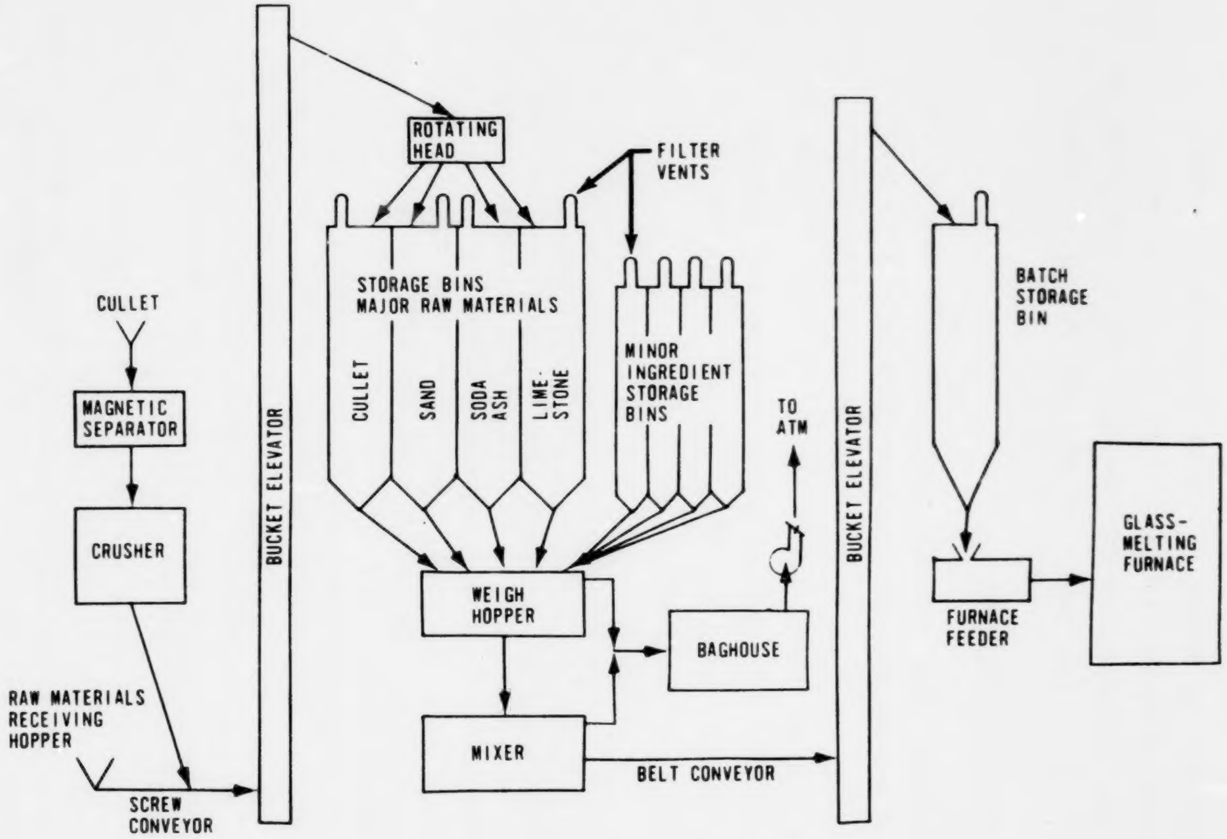
CULLET
MAGNETIC SEPARATOR
CRUSHER
RAW MATERIALS RECEIVING HOPPER
SCREW CONVEYOR
BUCKET ELEVATOR
ROTATING HEAD
FILTER VENTS
STORAGE BINS MAJOR RAW MATERIALS
CULLET
SAND
SODA ASH
LIME-STONE
MINOR INGREDIENT STORAGE BINS
WEIGH HOPPER
MIXER
BAGHOUSE
TO ATM
BELT CONVEYOR
BUCKET ELEVATOR
BATCH STORAGE BIN
FURNACE FEEDER
GLASS-MELTING FURNACE

Figure 3. Process flow diagram of a batch plant[12]

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[12] Danielson, J. A. Air Pollution Engineering Manual, 2nd Ed. Environmental Protection Agency. Research Triangle Park. Publication No. AP-40. May 1973. p. 765-782.

The various handling and mixing operations are a source of particulate emissions which are similar (same materials, same processes) to those in other industries.[12,13] Because of environmental and economic incentives, large manufacturers practice dust control by means of cloth filters and baghouses. Only limited data are available on particulate emissions from the preparation of raw materials, but they do indicate the generally low level of emissions (<0.05 g/kg).[14]

2. The Glass Melting Furnace

In the glass furnace, the various raw materials are melted together to form a homogeneous viscous liquid. A typical float glass melting tank is 46 m to 61 m long, 7 m to 9 m wide, and holds molten glass 1.2 m to 1.5 m deep (Figure 4). It contains 1,100 metric tons of molten glass and has a capacity of 400 metric tons per day. Sheet glass tanks average about half this capacity.[9,15-21]

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[13] A Screening Study to Develop Background Information to Determine the Significance of Glass Manufacturing. Prepared by The Research Triangle Park Institute for the Environmental Protection Agency. Research Triangle Park. Contract 68-02-0607, Task 3. December 1972.

[14] Point Source Listing for Glass, SCC 3-05-014, National Emission Data System. Environmental Protection Agency. Research Triangle Park. May 1974.

[15] Svec, J. J. LOF Operates World's Largest Glass Furnace. Ceramic Industry. 103(2):30-32, August 1974.

[16] Svec, J. J. Double Float Glass Line Produces 300 Million Square Feet. Ceramic Industry. 100:66-69, April 1973.

[17] Ford Motor Controls Glass Batch by Chemical Wetting. Ceramic Industry. 102:28-30, March 1974.

[18] Svec, J. J. Float Plant a Showcase at Pilkington. Ceramic Industry. 101(6):34-36, December 1973.

[19] Allen, A.C. New Canadian Plant Draws 14 Miles of Sheet Glass Per Day. Ceramic Industry. 91(6):52-54, December 1968.

[20] Allen, A. C. Canada Builds First Float Glass Plant. Ceramic Industry. 89(6):43-45, December 1967.

[21] Allen, A. C. One of the World's Largest Glass Tanks on Stream. Ceramic Industry. 89(4):50-51, October 1967.

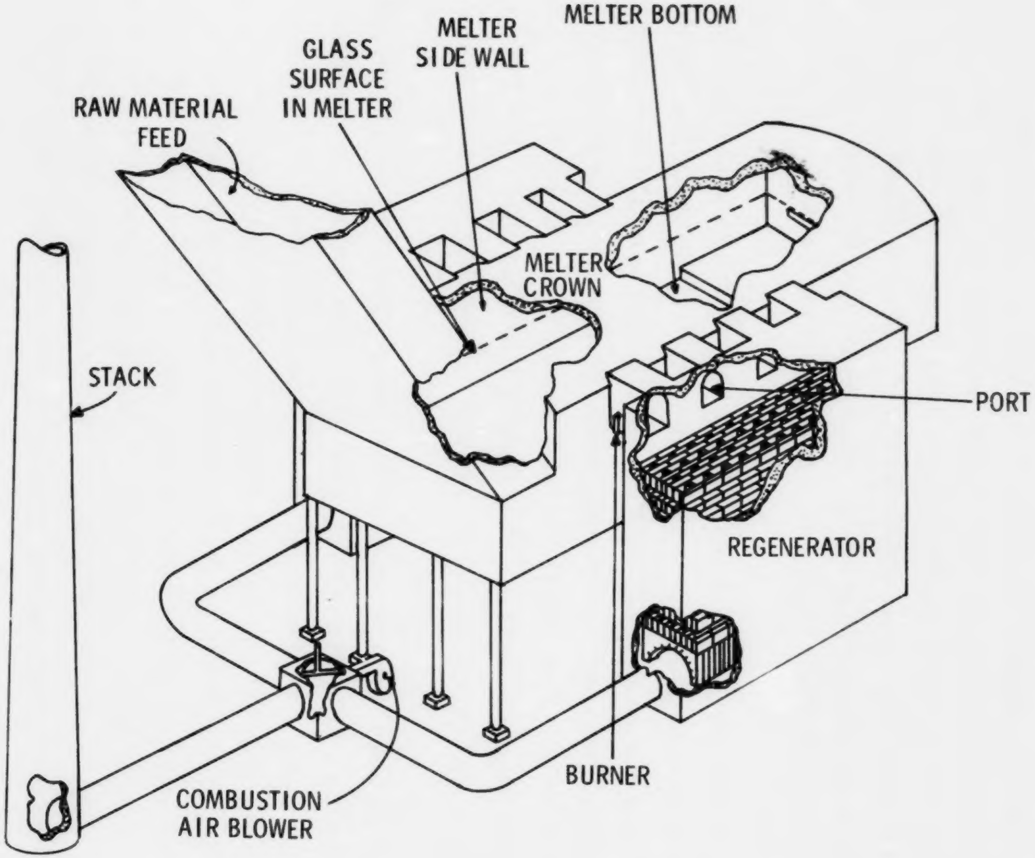
RAW MATERIAL FEED
GLASS SURFACE IN MELTER
MELTER SIDE WALL
MELTER BOTTOM
MELTER CROWN
STACK
PORT
REGENERATOR
BURNER
COMBUSTION AIR BLOWER

Figure 4. Regenerative side port glass-melting furnace[a]

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[a] After Reference 14.

In contrast to container glass furnaces, there is no throat (a refractory barrier with a submerged opening) dividing a flat glass tank into melting and conditioning sections. Rather, additional tank length (container glass tanks are only 15 m long) is needed to melt the glass.[9] Large melting tanks are also necessary in the float process so that the large quantity of molten glass can provide part of the heating energy for the tin float bath.[22] Sheet glass tanks may employ a fire-clay floater or water-cooled skimmer to separate the melting and working areas in the tank.

Raw materials are fed into one end of the furnace and layered on top of the molten glass. Temperatures in the melting section of the tank average 1,500°C. As the molten glass flows toward the other end of the tank, sand grains melt completely, gas bubbles rise to the surface, and convection currents produce a homogeneous melt. The temperature within the furnace gradually falls to 1,100°C as the glass leaves the tank.

Flat glass furnaces in the U.S. have been traditionally heated with natural gas, but gas shortages have led to an increased usage of oil. Gas is preferred because it causes less wear on the furnace and it is low in sulfur. Producers in the eastern part of the country may operate on oil for several months of the year. Electrical boosting is not used as a source of furnace heat. Although no data are available on the exact usage ratio of gas to oil, a 1973 breakdown of total energy used by the flat glass industry was as follows:[23]

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[22] Svec, J. J. Pilkington Manufacturers 2.3 mm Float Glass. Ceramic Industry. 103(1):36-37, July 1974.

[23] Schorr, J. R., and G. A. Anderson. Final Report on Industrial Energy Study of the Glass Industry. Prepared by Battelle for the Federal Energy Administration and the Department of Commerce. Washington. Contract 14-01-0001-1667. December 1974. p. 13-16,36.

Energy Form	Percent of Total Energy Used
Fuel oil	6.5
Natural gas	77.5
Electricity	14.9
Coal	1.1

After subtraction of the electricity and coal (which are not used to heat the furnace), the gas/oil ratio is 92% to 8%. Since 75% of the total energy is consumed by the melting furnace, this ratio should be close to the actual amount used in melting. One manufacturer reported using oil from 10% to 15% of the time.

The efficiency of glass furnaces is between 10% and 30%, with newer designs being more efficient. The theoretical heat for melting is ~1.85 MJ/kg.

Burners are placed on the sides of the tank furnace above the molten glass surface, and the burner flames are directed across the top of the melten glass. This side port configuration is used exclusively in flat glass furnaces since placing the burners at the feed end (end port design) is not feasible in a large long melting tank. To conserve fuel the typical furnace uses a regenerative firing system for heat recovery. Such a system consists of dual chambers filled with brick checkerwork on each side of the tank. While the products of combustion from the melter pass through and heat one chamber, combustion air is preheated in the opposite chamber. The functions of the chambers are interchanged during the reverse cycle. Reversals occur every 15 to 20 minutes as required for maximum conservation of heat.[9-12]

Emissions from the glass melting furnace include NO_x, SO_x, particulates, CO and hydrocarbons. Nitrogen oxides are formed by the reaction of atmospheric nitrogen at the high temperature conditions of the furnace. Sulfur oxides come from the volatilization of sulfates in the melt and, where fuel oil is used for heating, from the combustion of sulfur in the fuel. Particulate emissions may arise in two ways: (1) by the physical entrainment of dust by combustion gases when a batch is added to the furnace, and (2) by volatilization of materials in the melt which subsequently condense in the checkers or stack.[12,24,25] Carbon monoxide and hydrocarbons arise from incomplete fuel combustion and from coal in the glass batch.

3. Flat Glass Forming and Finishing Operations

Forming and finishing operations within the glass industry are very diverse and depend on the type of product being made. Flat glass products may be divided into four categories: float glass, sheet glass, rolled glass and plate glass. All are made by continuous processes from the initial drawing to cutting. The manufacturing steps used in the production of flat glass are outlined below. Figure 5 gives an overall flow diagram of the forming and finishing operations.

a. Float Process - The float glass process is a radical departure from all previous flat glass forming operations. The glass from the melting furnace may be rough rolled, pour drawn, or formed through a nozzle directly to a combined forming and finishing step. In this step the glass enters a sealed chamber containing a float bath of molten tin which is maintained under a neutral nitrogen atmosphere (Figure 6).

---

[24] Ryder, R. J., and J. J. McMackin. Some Factors Affecting Stack Emissions from a Glass Container Furnace. The Glass Industry. 50:307-310, June 1969; 346-350, July 1969.

[25] Arrandale, R. S. Pollution Control in Fuel-Fired Tanks. The Glass Industry. 55:12-13, 21, August 1974; 16-17,27, September 1974.

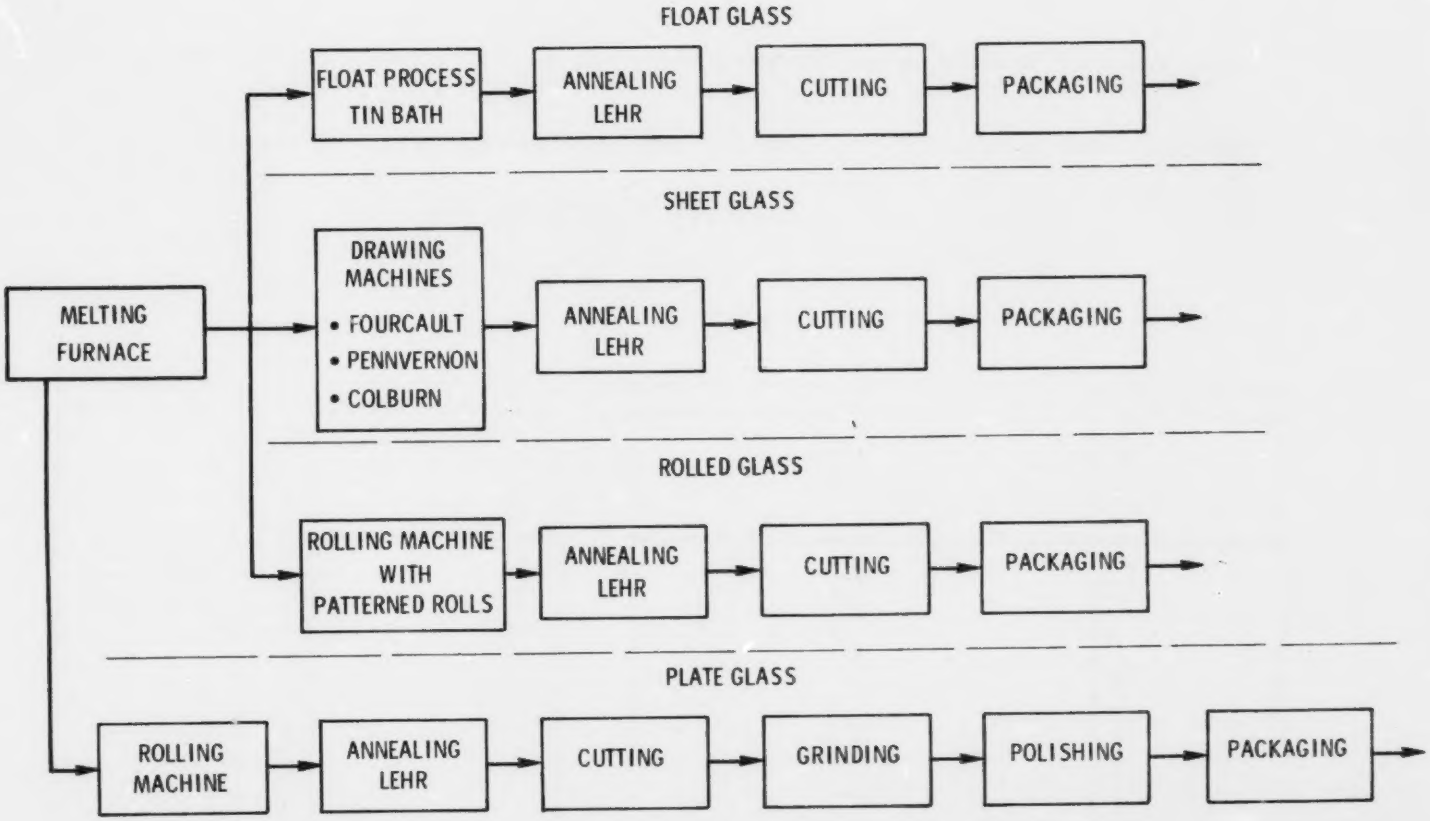
FLOAT GLASS
MELTING FURNACE
FLOAT PROCESS TIN BATH
ANNEALING LEHR
CUTTING
PACKAGING
SHEET GLASS
DRAWING MACHINES
• FOURCAULT
• PENNVERNON
• COLBURN
ANNEALING LEHR
CUTTING
PACKAGING
ROLLED GLASS
ROLLING MACHINE WITH PATTERNED ROLLS
ANNEALING LEHR
CUTTING
PACKAGING
PLATE GLASS
ROLLING MACHINE
ANNEALING LEHR
CUTTING
GRINDING
POLISHING
PACKAGING

Figure 5. Flow diagram of forming and finishing operations

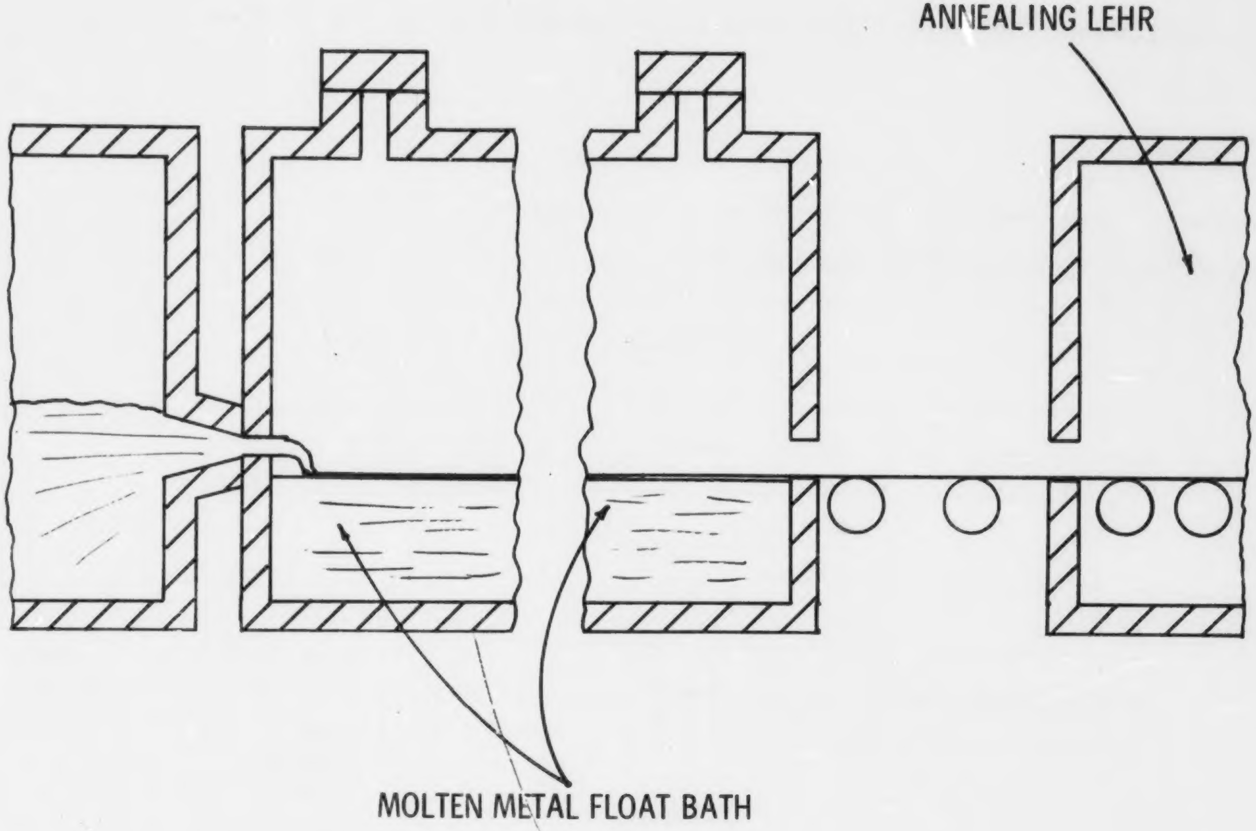
ANNEALING LEHR
MOLTEN METAL FLOAT BATH

Figure 6. Flat glass manufacturing: Pilkington float process[9]

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The glass flows onto and is drawn across the tin at a predetermined rate. The bath is temperature controlled in a way that permits the glass to flow and form a perfectly flat surface and then to harden before entering the annealing lehr.[9,15,16,18]

The tin bath is 60 m long and 64 mm to 76 mm deep. The temperature in the bath varies from 1,100°C at the hot end to 600°C at the cool end.[15,18]

The float process is very flexible and offers a number of outstanding advantages. It provides a finely finished surface to the glass without grinding and polishing. The lower surface of the glass is finished by the upper surface of the liquid metal while the upper surface of the glass is formed either by gravity or by a pool of molten metal located on the upper surface of the glass. The position of this pool remains constant while the sheet of glass passes underneath it. The pool of molten material is maintained in place by ridges on the edges of the glass sheet and by the speed of the glass through the chamber.

As the glass sheet leaves the float bath the lower surface may be sprayed with SO_2 to develop a protective coating of sodium sulfate. This prevents rollers in the annealing lehr from marring the smooth finish on the glass.[26]

Annealing is the process of preventing or removing objectionable stresses in glassware which result from too rapid cooling. It is carried out in long annealing lehrs which are precisely temperature controlled to give a predetermined cooling schedule. The lehr may be up to 150 m long and is heated with gas or electricity. Older lehrs are gas fired while some newer units use electricity for better temperature control.[9,16,27,28] Most float glass lehrs are heated electrically.

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[26] Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Flat Glass Segment of the Glass Manufacturing Point Source Category. U.S. Environmental Protection Agency. Washington. EPA-44011-74-001-C. January 1974. p. 44.

The glass sheet passes through the annealing lehr and is then cut, inspected, and stored for shipment.

b. Sheet Glass - Sheet glass is produced by continuous drawing operations of which there are three types.

(1) Fourcault process - The Fourcault process (Figure 7) is a vertical draw process as are the two discussed below. The major feature of this drawing process is the debiteuse, a rectangular refractory collar which is partially submerged in the glass melt. In the collar there is a slot 100 mm to 200 mm wide and up to 2.4 m long. Molten glass is drawn upwards from the slot by powered rollers located in a vertical annealing lehr 7.6 m high. The speed at which the sheet is drawn and the width of the slot in the debiteuse determine the thickness of the glass sheet. The annealing lehr provides controlled cooling of the sheet to prevent cracking, stressing, or visual distortion of the final product.[8-11]

After the sheet emerges from the top of the annealing lehr it is cut to size, inspected for flaws, and stacked for shipment.

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[27] Fuller, R. A. Recirculating Lehr for Annealing Glassware. Ceramic Bulletin. 48:1065-1068, November 1969.

[28] Roos, P. W. Lehr Priority: Design Concepts to Save Energy. The Glass Industry. 56:18-22, April 1975.

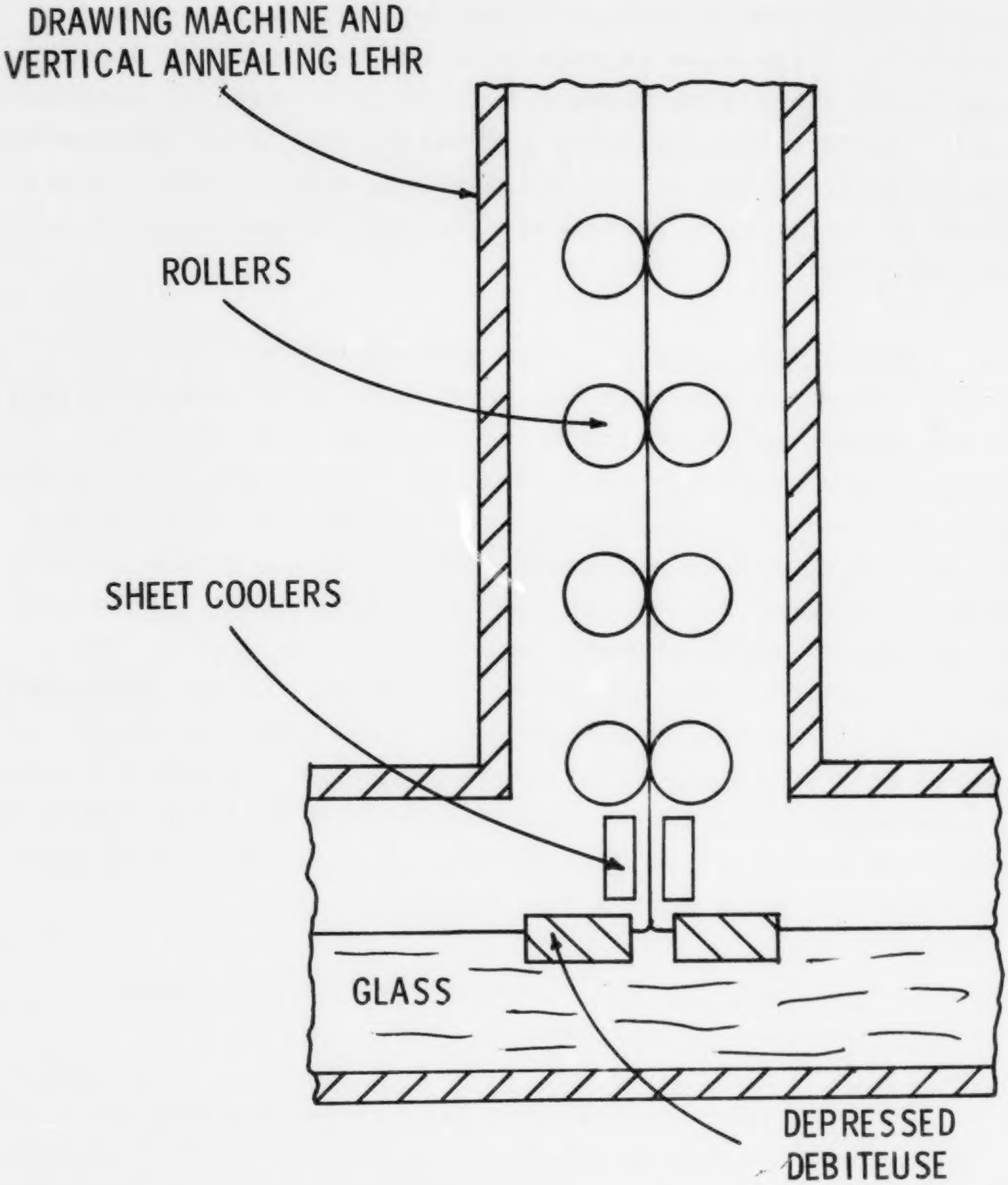
DRAWING MACHINE AND
VERTICAL ANNEALING LEHR
ROLLERS
SHEET COOLERS
GLASS
DEPRESSED
DEBITEUSE

Figure 7. Flat glass manufacturing: Fourcault process[9]

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(2) PPG Pennvernon process - The only difference between this process and the Fourcault process is the method by which the glass leaves the surface of the melt. In place of a debiteuse this process uses a totally submerged refractory drawbar (Figure 8). The draw is made from the melt surface directly over the bar and then through rollers in a vertical annealing lehr. The drawbar partially conditions the glass, determines the point of origin of the glass sheet, and reduces irregularities in the product resulting from convection currents in the melt.[8-11]

(3) LOF-Colburn process - This process differs from the others described above in two ways. One difference consists of the method by which the sheet is drawn from the melt. Instead of a debiteuse or drawbar to control the size of the draw, rollers pull the glass directly from the melt (Figure 9). It is therefore necessary to place cooling edge rollers close to the surface of the melt to help control the thickness of the sheet and to prevent necking down the sheet. The second difference between this process and the two described above is in the use of a horizontal annealing lehr which requires that the sheet of glass be bent over rollers 1 m above the surface of the melt. This is the last possible moment at which the glass can be bent without damage. From this point the sheet of glass enters the annealing lehr.[8-11]

The above three processes all have the same annealing, cutting, inspection, and storage steps.

c. Rolled Glass - In this process, glass is taken directly from the melting furnace by a set of rollers which form the glass into a sheet (Figure 10). From these primary rollers the glass sheet is taken into an annealing oven before it becomes inflexible. The design for patterned or frosted window glass is imprinted on one or both of the rollers drawing

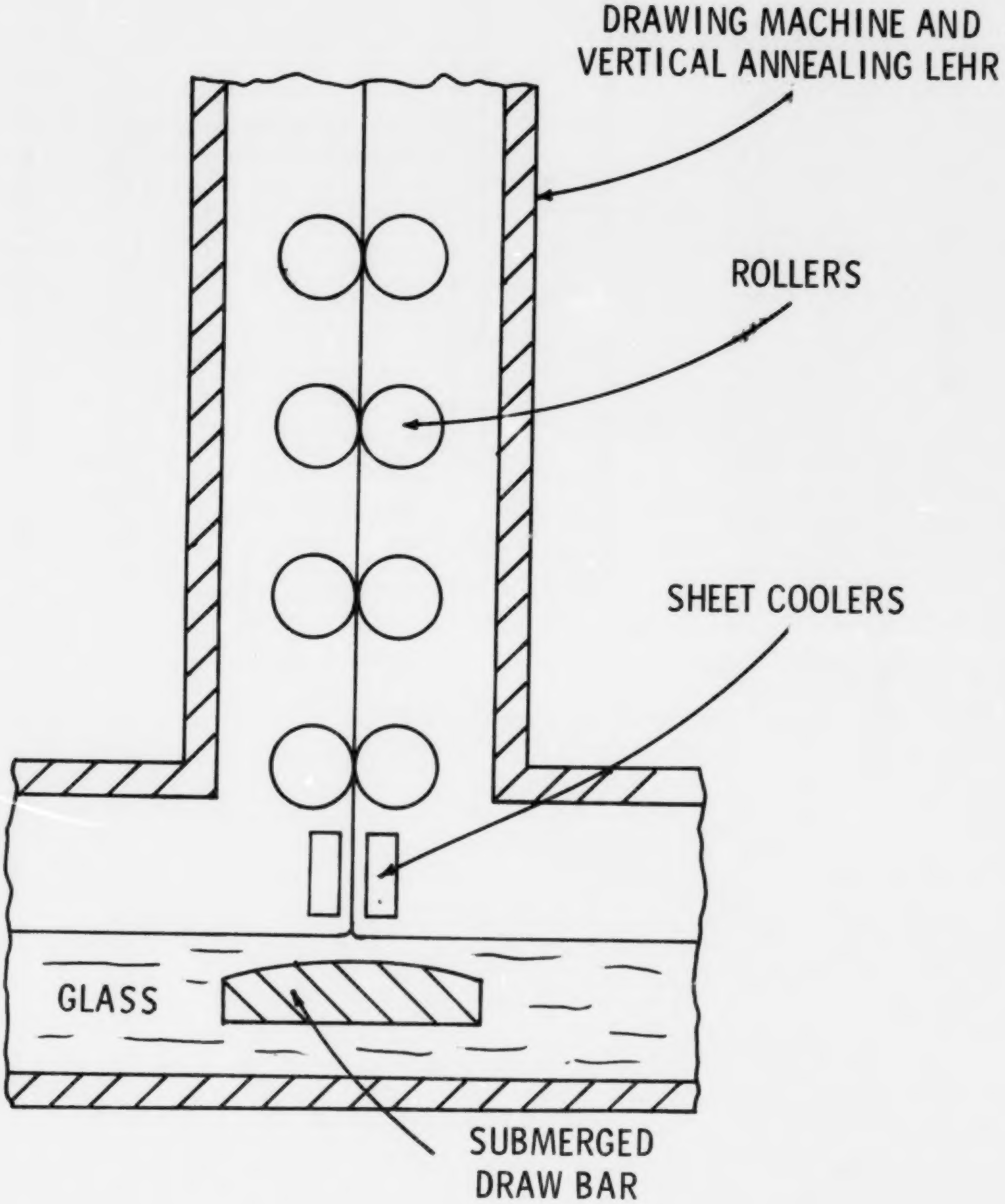
DRAWING MACHINE AND
VERTICAL ANNEALING LEHR
ROLLERS
SHEET COOLERS
GLASS
SUBMERGED
DRAW BAR

Figure 8. Flat glass manufacturing: PPG Pennvernon process[9]

Reprinted by permissions of The Glass Industry and PPG Industries, Inc.

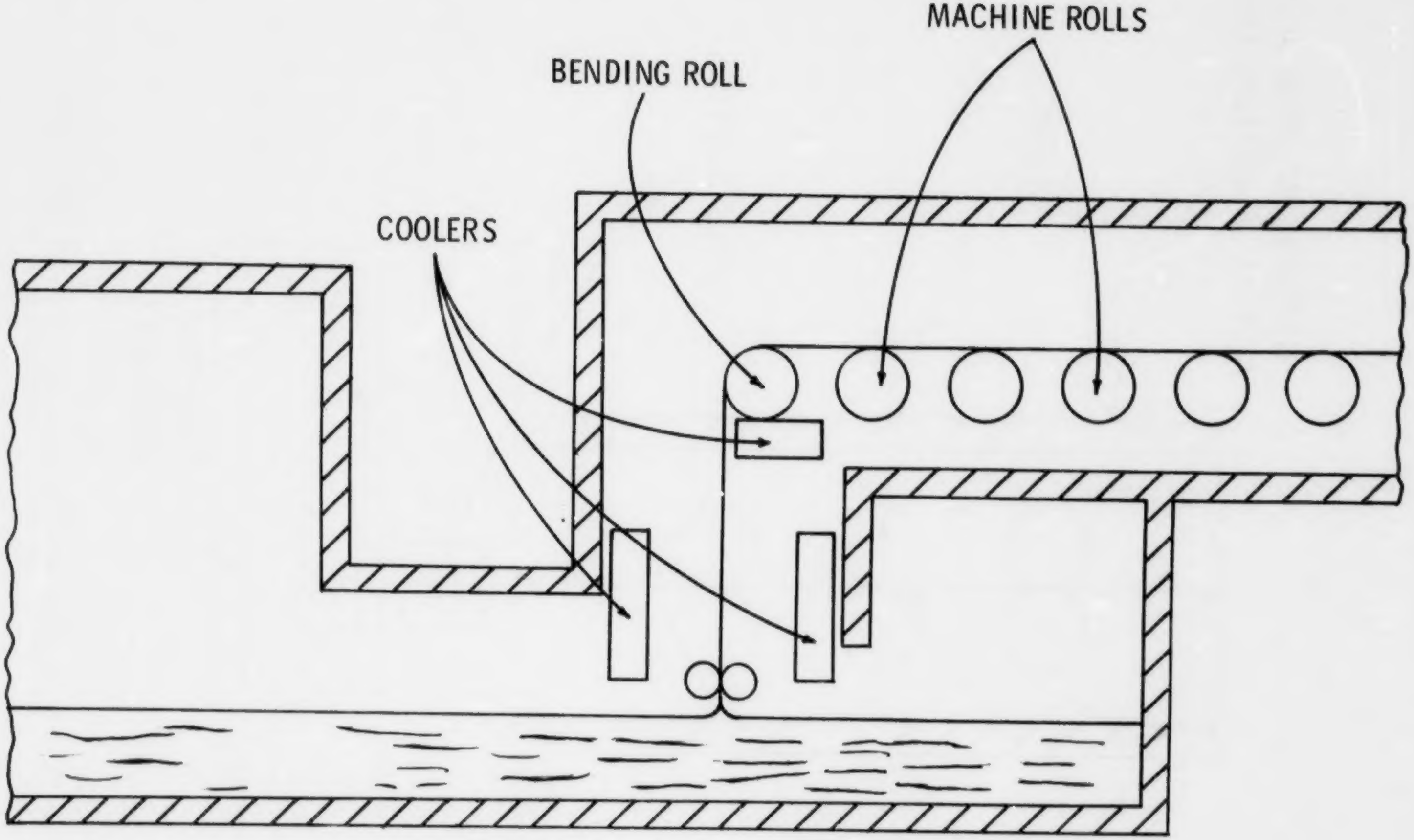
MACHINE ROLLS
BENDING ROLL
COOLERS

Figure 9. Flat glass manufacturing: LOF-Colburn process[9]

Reprinted by permissions of Van Nostrand Reinhold Co. and Libbey-Owens-Ford Glass Co.

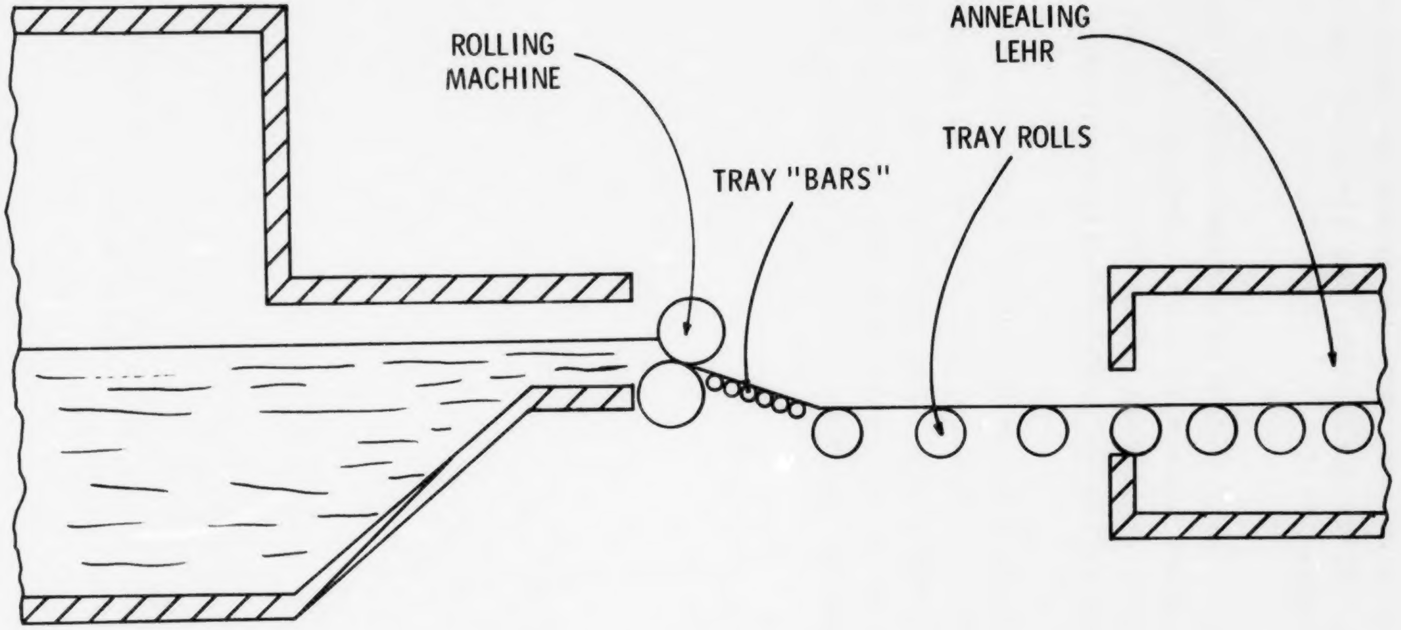
ROLLING MACHINE
TRAY "BARS"
TRAY ROLLS
ANNEALING LEHR

Figure 10. Flat glass manufacturing: rolling process[9]

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the glass from the furnace. Wired safety glass is formed by feeding a roll of wire mesh into the glass in front of the primary rollers. After annealing, the glass is cut and packaged for shipment.[8-11]

d. Plate Glass - Plate glass is manufactured by the rolling process using smooth rollers. Because the rollers introduce surface distortions, plate glass is ground and polished after annealing to produce a smooth surface.

e. Emission Points - In general, the forming and finishing operations in flat glass manufacture do not cause emissions directly to the atmosphere. The processes take place within the plant building and any emissions are released inside the building. Combustion products from the annealing lehr are an exception.

SECTION IV

EMISSIONS

A. SELECTED POLLUTANTS

The manufacture of glass gives rise to air emissions during each phase of production.

- The preparation of raw materials is a source of particulate emissions.
- The glass melting furnace emits NO_x, SO_x, particulates, CO and hydrocarbons.
- The only emissions in forming and finishing operations are combustion products from gas-fired annealing lehrs.

1. Raw Materials Preparation

Points of emission in the preparation of raw materials are identified in Figure 7. These have been classified into five general groups:

- Handling of raw materials (unloading and conveying)
- Crushing of scrap glass
- Filling and emptying of storage bins
- Batch mixing (and weighing)
- Feeding of mixed glass batch to melting furnace (batch charger)

Although all of these operations are potential sources of particulate emissions, at least 90% of the industry has installed dust controls. Handling operations are enclosed

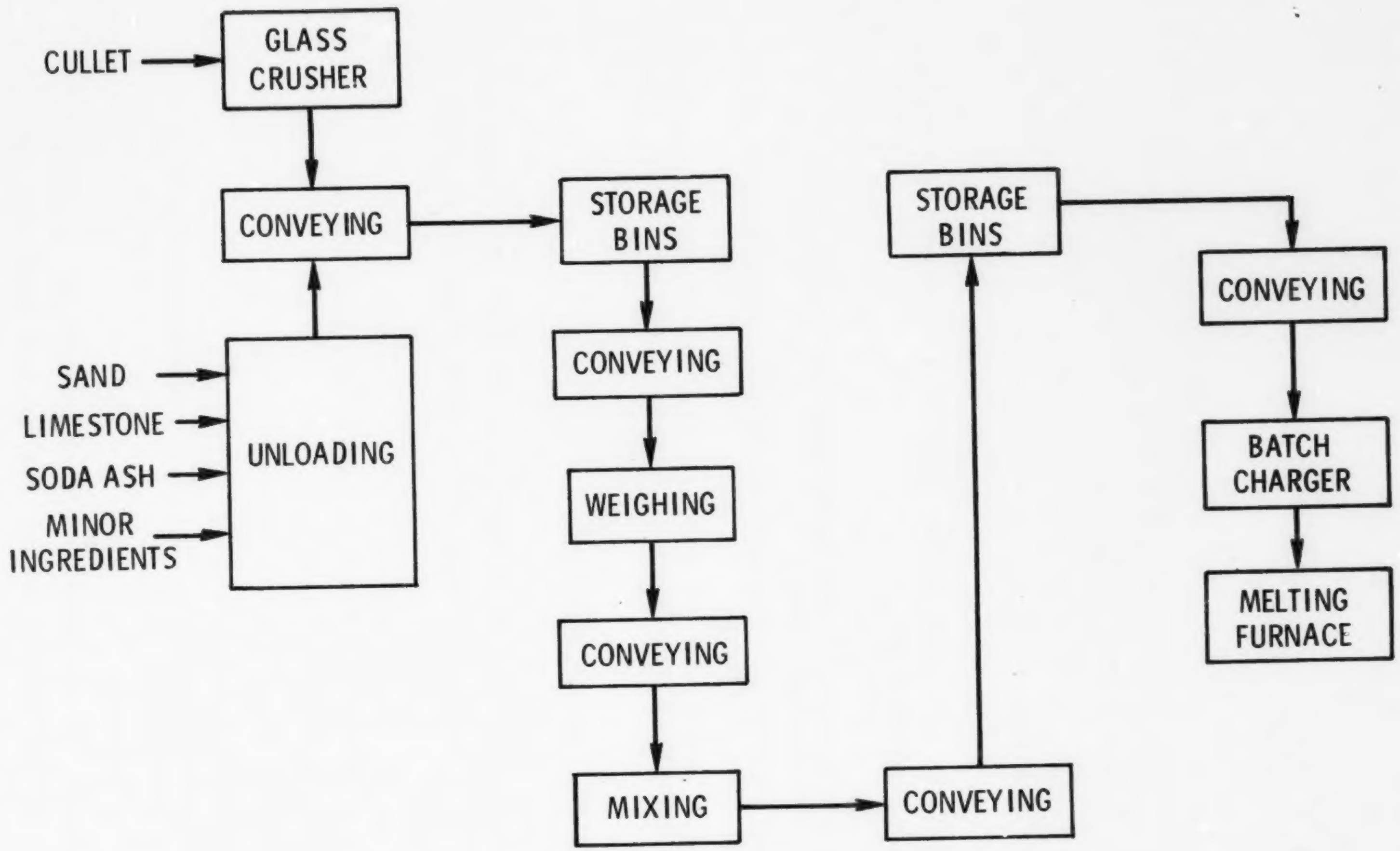
CULLET
GLASS CRUSHER
CONVEYING
SAND
LIMESTONE
SODA ASH
MINOR INGREDIENTS
UNLOADING
STORAGE BINS
CONVEYING
WEIGHING
CONVEYING
MIXING
CONVEYING
STORAGE BINS
CONVEYING
BATCH CHARGER
MELTING FURNACE

Figure 11. Points of emission during the preparation of raw materials (All of these steps are potential sources of particulate emissions.)

to eliminate fugitive emissions and vents on storage bins and mixers are exhausted through baghouses. In addition, the particle size of the raw materials is chosen to minimize dusting, and water is added to the mixed batch. Because of this, there are few data available on particulate emissions from stacks and no data on fugitive emissions.

Source test data that have been reported in NEDS (National Emission Data System) are given in Appendix C. The resulting average emission factors are given in Table 7 along with total industry emissions. The zero emission factors for handling and batch charging were determined during a personal visit to a large float glass plant. Handling operations were either completely enclosed or performed within the plant building, and no fugitive dust emissions were visible. The batch charger was partially enclosed and situated inside the plant. No dust could be seen in the charging area (the mixed batch had been moistened to alleviate dusting and to prevent the segregation of raw materials in the batch).

The overall emission factor is 0.02 g/kg ± 100% and total particulate emissions are 90 metric tons ± 100%. The composition of the particulate emissions will be that of the raw materials (basically sand, lime, and soda ash) since no chemical reactions take place. As discussed in Section V on control technology, glass sand is processed to remove <44-μm (minus 325-mesh) material. Consequently, there will be no respirable quartz in the emissions.

2. Glass Melting Furnace

The different species emitted from the glass melting furnace are listed in Table 8 along with their average emission factors and total yearly emissions. Emission factors are based on test results from container glass furnaces and pressed and

Table 7. PARTICULATE EMISSIONS DURING THE PREPARATION OF RAW MATERIALS

Process step	Emission factor, g/kg	Material processed, 10^6 metric tons	Total emissions, metric tons
Handling (unloading, conveying)	0	4.5	0
Glass crusher	0.0123 ± 100%	1.8	22 ± 22
Storage bins	0.0123 ± 100%	4.5	55 ± 55
Mixing (and weighing)	0.00158 ± 106%	4.5	7 ± 7
Batch charger	0	4.5	0
TOTAL (Independent rounding)	0.02 ± 100%	4.5	90 ± 90

Table 8. EMISSIONS FROM THE GLASS MELTING FURNACE

Species	Emission factor, g/kg	Glass produced, 10^6 metric tons	Total emissions, 10^3 metric tons
NO_x	4 ± 30%	4.0	16.0 ± 4.8
SO_x	1.5 ± 27%	4.0	6.0 ± 1.62
Particulates	1 ± 60%	4.0	4.0 ± 2.4
CO	0.02 ± 100%	4.0	0.080 ± 0.080
Hydrocarbons	0.04 ± 100%	4.0	0.160 ± 0.160

blown glass furnaces, in addition to flat glass furnaces, since the melting process is the same for all soda-lime glasses (i.e., same melt temperatures and major raw materials). However, other emissions which may arise from minor ingredients in the melt (e.g., fluoride or borate) are not present in stack gases from flat glass furnaces. While chlorine is present as a batch impurity (∿0.06 g/kg as NaCl), it has not been detected in the furnace exhaust.

The parameters that affect emissions are considered in more detail in Section V under Process Modifications. In general, the furnace temperature and the batch raw materials are the two key process variables. Oil vs. gas firing is also important when oil heating is practiced (∿10% of the time). Secondary factors relate to overall furnace efficiency and may include combustion conditions, age of furnace and checkerwork, type of refractories used in the furnace, and checkerwork design.

a. Nitrogen Oxides - Nitrogen oxides represent the largest fraction by mass (∿61%) of glass furnace emissions. They are formed by the combination of atmospheric nitrogen and oxygen at the high temperatures (1,500°C) within the melting furnace. The reaction is very temperature sensitive, as indicated in one study where the NO_x concentration in the stack gas increased sixfold (from 100 ppm to ~600 ppm) when the production rate was doubled (from 90 to 180 metric tons/day) and the furnace temperature increased from 1,460°C to 1,551°C.[24,29]

Source test measurements reported in NEDS give an average emission factor of 4 g/kg, with individual values ranging from 0.71 to 10.5 g/kg.[14] The average is based on 27 values representing ~9% of total U.S. glass production (see Appendix C.2). The average is accurate within ±1.2 g/kg at a 95% confidence level.

One large flat glass manufacturer reported that furnaces are presently operating at higher efficiencies than in the past. Since the test data in Appendix A are primarily from 1970 - 1972, they may overestimate the average NO_x emission factor.

b. Sulfur Oxides - Sulfur oxide emissions result from the decomposition of sulfates in the melt and from the oxidation of sulfur in the fuel. Consequently, the emission factor will depend on the sulfur content of the feed material and fuel, and the furnace temperature. Sodium sulfate is used as a fluxing agent in the glass batch (~2% by weight) and decomposes above ~1,000°C to Na_2O and SO_3. Above 1,200°C, SO_3 is unstable with respect to SO_2 and O_2. Not all the sulfur oxides are emitted as such; some (~25%) combine with

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[29] Control Techniques for Nitrogen Oxide Emissions from Stationary Sources. U.S. Department of Health, Education and Welfare. Washington. NAPCA Publication No. AP-67 (PB 190265). March 1970. 115 p.

sodium vapor [presumably in the form of sodium hydroxide dimer, $Na_2(OH)_2$] to form Na_2SO_4.[30]

If sulfur is present in the fuel it will oxidize and appear as SO_x in the exhaust gas. A fuel oil containing 1% sulfur by weight will give $\sim$600 ppm SO_2 in the flue gas.[31] The emission factor can be calculated on the basis of a heating value of 41.9 GJ/m^3 of fuel oil and a 30% furnace efficiency. (About 1.85 MJ are needed to make a kilogram of glass.)[9] The $\sim$100 liters of fuel oil needed to melt a metric ton of glass contain $\sim$1.2 kg of sulfur. If all the sulfur were oxidized to SO_2, the emission factor would be $\sim$2.6 g/kg. It will actually be less than this because of conversion to Na_2SO_4.

Source test measurements for SO_x emissions range from 0.2 to 4.4 g/kg. The average emission factor is 1.5 g/kg, based on NEDS data from 12% of total U.S. production. This value is accurate to ±0.4 g/kg at a 95% confidence level. Detailed data are presented in Appendix C.2. As previously mentioned, the present day average emission factor may be lower than 1.5 g/kg because of improved furnace operation.

c. Particulates - Particulate emissions in glass furnaces result from (1) the physical entrainment of dust from the feed material in hot combustion gases, and (2) the volatilization of sulfates in the melt which later condense as they leave the furnace. Data show that large sized particles (>1 μm) generated by the first mechanism are trapped in the regenerative checkerwork and do not go out the stack,[12,24,25] as evidenced by:

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[30] Davis, R. E., W. H. Manring, and W. C. Bauer. Carryover Studies in Glass Furnaces. In: Collected Papers from the 34th Annual Conference on Glass Problems. Dept. of Ceramic Engineering, University of Illinois, Urbana, November 1973. p. 109-126.

[31] Reed, R. H. Combustion Pollution in the Glass Industry. The Glass Industry. 54:24,26,38, April 1973.

- Analysis of dust collected in the checkers which shows that it resembles the feed material (high silica, e.g.). Dust going out the stack is primarily alkali sulfate.[12,25,32]
- Dust trapped in the checkers is micron size, but dust leaving the stack is submicron size.[12,33]
- The emission rate increases as the furnace temperature increases. (The logarithm of the emission factor decreases in direct proportion to the reciprocal of the absolute temperature.)[24,34]

Submicron particulates are formed from condensed vapors from the glass melt in accordance with the second mechanism indicated.[13,25,30,35]

Source test measurements in NEDS of particulate emissions factors vary from 0.22 to 8.3 g/kg (see Appendix C.2), with an average of 1 g/kg based on ∿19% of total U.S. production. This is identical to the emission factor given in the

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[32] Mills, H. N., and J. Jasinski. Evaluating Batch Changes. The Glass Industry. 51:223-227, May 1970.

[33] Stockham, J. D. The Composition of Glass Furnace Emissions. Journal of the Air Pollution Control Association. 21:713-715, November 1971.

[34] Arrandale, R. S. Air Pollution Control in Glass Melting. Symposium Sur La Fusion du Verre, Brussels. October 1968. p. 619-644.

[35] Custer, W. W. Electrostatic Cleaning of Emissions from Lead, Borosilicate, and Soda-Lime Glass Furnaces. United McGill Corp. (Presented at the 35th Annual Conference on Glass Problems. Ohio State University, Columbus, November 14-15, 1974.) 13 p.

Compilation of Air Pollution Emission Factors (AP-42).[36] The value of 1 g/kg is accurate within ±0.6 g/kg at a 95% confidence level. Because of improved furnace efficiency, the current average factor may be lower than 1 g/kg.

The composition of particulate emissions from soda-lime glass furnaces is primarily (∿80%) sodium sulfate.[12,24,25,30,33] The other elements found in the particulate vary greatly and reflect variations in the feed composition. Since flat glass does not contain ingredients such as boron, fluoride, and arsenic, these are absent in the particulates. One analysis of flat glass particulates showed 98% Na_2SO_4.[a]

d. Carbon Monoxide - Carbon monoxide is emitted from two sources in the glass melting furnace: (1) incomplete combustion of fuel, and (2) reaction of coal used as a reducing agent in the glass batch. Powdered coal is added to the batch to reduce sulfates to sulfites; the carbon is oxidized to CO or CO_2. The amount varies from 5% to 10% by weight of the sulfate content of the batch,[37] or about 1.5 g coal/kg raw materials for a mix containing 2.2% Na_2SO_4.

The average emission factor based on two sets of measurements is 0.02 g/kg ± 100% (Appendix C.2). The accuracy is estimated because assumptions had to be made in the calculations. For comparison another emission factor was calculated based

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[a] Information supplied by a flat glass manufacturer.

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[36] Compilation of Air Pollution Emission Factors, Second Edition. Environmental Protection Agency. Washington. Publication No. AP-42. April 1973. p. 8.13-1.

[37] 1974 Annual Raw Material Processing Handbook. Ceramic Industry. 102:97, January 1974.

on CO emissions data from gas-fired burners. This value is 0.066 g/kg ± 55%. Details are given in Appendix C.2. Emissions of both CO and hydrocarbons are strongly dependent on combustion conditions, and improper mixing of air and fuel or mixing without enough oxygen can raise the emission rate by a factor of 10 or more.

e. Hydrocarbons - Hydrocarbons form in glass furnaces in the same way that CO does: by incomplete fuel combustion and by decomposition of powdered coal in the melt. The emission factor based on one set of measurements is 0.04 g/kg ± 100% (Appendix C.2). The accuracy was determined as it was for the CO factor. For comparison the emission factor based on data from gas-fired burners is 0.042 g/kg ± 144%. Details appear in Appendix C.2.

3. Forming and Finishing Operations

The only atmospheric emissions from flat glass forming and finishing operations are combustion products from gas-fired annealing lehrs. A plant visit established that other processes are not emission sources. The machinery that is used does not bring the hot glass into contact with lubricated surfaces, as is true in the production of glass containers, so no lubricants are vaporized. The float glass tin bath is totally enclosed except for openings at either end where the glass sheet enters and leaves. No emissions are visible from the openings, and a material balance on the tin bath shows that possible losses to the atmosphere are less than 0.001 g of tin per kg glass melted. As the glass sheet leaves the float bath, the hot surface is sprayed with SO_2 which reacts to form a protective coating of Na_2SO_4. There is no detectable odor of SO_2 in the vicinity of this operation and it is concluded that all the SO_2 reacts to form the sulfate.

Annealing lehrs provide controlled cooling of glass products. Thus their only emissions are combustion products. Since these have never been measured, emission factors were estimated from other data on gas combustion (see Appendix C.3). The results are given in Table 9. Although the majority of plants use electrically heated lehrs, the exact percentage of use is unknown. Total national emissions were therefore calculated on a worst case condition of 50% gas firing.

Table 9. EMISSIONS FROM GAS-FIRED ANNEALING LEHRS

Emissions	Emission factor, g/kg	Glass annealed, 10^6 metric tons	Total emissions, metric tons
NO_x	0.016 ± 113%	2.0	32 ± 36
SO_x	0	2.0	0
Particulates	0.0012 ± 196%	2.0	2 ± 5
CO	0.0022 ± 55%	2.0	4 ± 2
Hydrocarbons	0.0014 ± 144%	2.0	3 ± 4

B. EMISSION CHARACTERISTICS

1. Raw Materials Preparation

Emissions of particulates are composed of sand, soda ash, limestone, sodium sulfate, and glass dust. The exact composition has never been measured. The materials that tend to dust most easily are the sodium compounds and limestone since they are soft and crush readily. Glass sand does not cause dusting and it has been processed to remove <44-μm (minus 325-mesh) particles.

The primary ambient air standard for particulates is 260 $\mu g/m^3$. Materials for which threshold limit values

(TLVs®) have been established include limestone (10 mg/m^3) and glass dust (10 mg/m^3).[38]

Sand and glass dust are stable compounds while soda ash and limestone, being slightly basic, may react with SO_x in the atmosphere.

2. Glass Melting Furnace

Emissions from the melting furnace consist of the criteria pollutants: NO_x, SO_x, particulates, CO, and hydrocarbons. These materials interact in the formation of photochemical smog while NO_x and SO_x are irritating to the lungs. The ambient air standards and TLV's for these compounds are given in Table 10.

A question has recently arisen concerning the possible health effects from particulate sulfate emissions. Since glass furnace particulates are primarily (98%) sodium sulfate, they may pose some health hazard. It is unclear at this time, however, whether the health effects stem from the sulfate ion or the associated metal ion. No TLV has been established for sodium sulfate.

3. Forming and Finishing Operations

The emissions from forming and finishing operations are combustion products from gas-fired annealing lehrs. These are the same criteria pollutants discussed in Section 2 above.

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[38] TLVs® Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment with Intended Changes for 1975. American Conference of Governmental Industrial Hygienists. Cincinnati. 1975. 97 p.

Table 10. CHARACTERISTICS OF EMISSIONS FROM GLASS MELTING FURNACE

Compound	TLV, mg/m^3	Ambient air quality standard[39]		Health effects	Atmospheric stability
		mg/m^3	Averaging time		
NO_x	9 (for NO_2)	0.100	Annual arithmetic mean	Dangerous irritant to lungs	Contributes to photochemical smog
SO_x	13 (for SO_2)	0.365	24 hr; not to be exceeded more than once per year	Dangerous irritant to lungs	Contributes to photochemical smog; also forms acid mist
Particulate	10	0.260	24 hr; not to be exceeded more than once per year	Unknown	Stable
CO	55	40	1 hr; not to be exceeded more than once per year	High concentrations (1000 ppm) are asphyxiating	Stable
Hydrocarbons	(1000 ppm for methane)	0.160	3 hr; 6-9 AM	Simple asphyxiant	Contributes to photochemical smog

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[39] Code of Federal Regulations, Title 42 - Public Health, Chapter IV - Environmental Protection Agency, Part 410 - National Primary and Secondary Ambient Air Quality Standards, April 28, 1971. 16 p.

C. ENVIRONMENTAL EFFECTS

1. Total Emissions

Total emissions from flat glass manufacturing are shown in Table 11. The melting furnace contributes the largest amount of emissions (99%), and NO_x, SO_x, and particulates are the only significant emissions ($>10^3$ metric tons).

Table 11. TOTAL EMISSIONS
(metric tons/yr)

Source	NO_x	SO_x	Particulates	CO	Hydrocarbons
Raw materials preparation	0	0	90	0	0
Melting furnace	16,000	6,000	4,000	80	160
Annealing lehr	32	0	2	4	3
TOTAL	16,000	6,000	4,000	80	160

When total flat glass emissions are compared to total national emissions from all stationary sources, they are all less than 0.1% (NO_x = 0.07%, SO_x = 0.02%, and particulates = 0.02%). On a statewide basis the largest contributions are from NO_x emissions in Tennessee (0.6%) and Oklahoma (0.5%). A detailed breakdown can be found in Appendix D.

2. Ground Level Concentrations

As an aid to evaluating the environmental effects of stack emissions, a plume dispersion equation was used to calculate the maximum average ground level concentration, $\overline{\chi}_{max}$, of each emission species around a representative flat glass plant. The representative plant has a production rate of 500 metric tons/day and emission rates as shown in Table 8. The plant makes float glass in a side port regenerative furnace and uses natural gas for heating. Only furnace emissions were considered since they account for over 99% of plant emissions. Two average stack heights (30 m and 60 m) were used in the calculations since a tabulation of stack heights (Table 12) showed a bimodal distribution. The taller stacks are natural draft while the shorter ones use an ejection air system. (Some of the tall stacks have been converted from natural draft to ejection air.)

Table 12. STACK HEIGHTS OF FLAT GLASS FURNACES,[14]
(meters)

Stacks under 40 m	Stacks over 40 m
18	46
23	46
24	48
32	49
32	52
32	56
32	61
32	61
34	61
34	61
34	63
34	63
	64
	65
	67
	76
	84
	84
Average = 30	Average = 60

The values of $\overline{\chi}_{max}$ were computed from the equation suggested by Turner:[40]

$$\overline{\chi}_{max} = \chi_{max} \left(\frac{t_0}{t}\right)^{0.17} \qquad (1)$$

$$\chi_{max} = \frac{2\ Q}{\pi e u H^2} \qquad (2)$$

where Q = emission rate, g/s
H = effective stack height, m
$\pi = 3.14$
$e = 2.72$
u = wind speed, m/s
= 4.5 m/s (national average)
χ_{max} = "instantaneous" (i.e., 3-minute average) maximum ground level concentration
t_0 = 3 minutes
t = averaging time, minutes

The averaging time chosen for each emission was the same as for the corresponding ambient air quality standard (AAQS). The effective stack height is equal to the physical stack height plus the plume rise (see Appendix E for a determination of the plume rise correction). A source severity, S, was then defined as the ratio of $\overline{\chi}_{max}$ to the standard:

$$S \equiv \frac{\overline{\chi}_{max}}{AAQS} \qquad (3)$$

Equations for S are given in Appendix F.

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[40] Turner, D. B. Workbook of Atmospheric Dispersion Estimates, 1970 Revision. U.S. Department of Health, Education and Welfare. Cincinnati. Public Health Service Publication No. 999-AP-26. May 1970. 84 p.

Values of $\bar{\chi}_{max}$ and S for flat glass emissions are given in Table 13. The highest values are for NO_x emissions (S = 1.3 for a 30 m stack). The severity for both CO and hydrocarbons is ≤0.01.

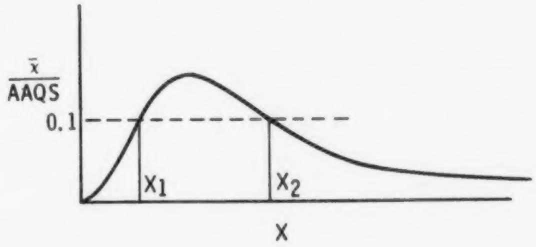
Table 13. SOURCE SEVERITY FOR FLAT GLASS EMISSIONS

Emission	Ambient air quality standard, mg/m^3	$\bar{\chi}_{max}$, $\mu g/m^3$		S	
		Stack height[a] = 30 m	Stack height[a] = 60 m	Stack height[a] = 30 m	Stack height[a] = 60 m
NO_x	0.100	130	57	1.3	0.57
SO_x	0.365	44	20	0.12	0.05
Particulates	0.260	29	13	0.11	0.05
CO	40.0	1.0	0.45	<0.01	<0.01
Hydrocarbons	0.160	1.7	0.74	0.01	<0.01

[a] Effective stack height is 30 m higher due to plume rise.

3. Affected Population

Dispersion equations predict that the average ground level concentration ($\bar{\chi}$) varies with the distance, x, away from a source. For elevated sources, $\bar{\chi}$ is zero at the source, increases to some maximum value, $\bar{\chi}_{max}$, as x increases, and then falls back to zero as x approaches infinity. Therefore a plot of $\bar{\chi}$/AAQS vs. x will have the following appearance:



The affected population is defined as the population around a representative plant exposed to a $\overline{\chi}$/AAQS ratio > 0.1 or 1.0. The mathematical derivation of the affected population can be found in Appendix F. Results for flat glass furnace emissions are given in Table 14. The largest population affected is for NO_x emissions from a 30 m stack (14,600) persons).

Table 14. AFFECTED POPULATION

Emission	$\overline{\chi}$/AAQS > 0.1			
	Affected area, km^2		Affected population[a]	
	Stack height[b] = 30 m	Stack height[b] = 60 m	Stack height[b] = 30 m	Stack height[b] = 60 m
NO_x	59.0	55.8	14,600	13,800
SO_x	3.0	0	750	0
Particulates	2.6	0	640	0
CO	0	0	0	0
Hydrocarbons	0	0	0	0
	$\overline{\chi}$/AAQS > 1.0			
NO_x	2.8	0	703	0
SO_x	0	0	0	0
Particulates	0	0	0	0
CO	0	0	0	0
Hydrocarbons	0	0	0	0

[a] Based on an average population density of 248 persons/km^2.

[b] Effective stack height is 30 m higher due to plume rise.

SECTION V

CONTROL TECHNOLOGY

Economic and environmental considerations have motivated the glass industry to develop methods for reducing air emissions from the manufacturing process. Two general approaches have been employed: (1) the use of air pollution control equipment, and (2) changes in the production process. An example of the first approach is the use of baghouses to control particulate emissions from raw material mixing operations. The other method is typified by the reduction of volatile materials such as sodium sulfate in the glass batch, resulting in lower particulate emissions from the melting furnace.

A. PREPARATION OF RAW MATERIALS

The handling and mixing of raw materials is a source of particulate emissions. The problem is similar to that in other industries using granular or powdery materials, and standard control techniques are available.[12] These are summarized in Table 15.

Railroad hopper cars and hopper bottom trucks can be connected to sealed receiving hoppers by fabric sleeves so that dust generated in the hoppers during the loading operation is either filtered through the sleeves or exhausted through a baghouse. Dust control equipment can be installed

Table 15. PARTICULATE CONTROLS FOR THE PREPARATION OF RAW MATERIALS

Control technique	Efficiency	Advantages	Disadvantages
Control equipment			
Enclosing all handling operations	100%	Eliminates all dusting	Added cost for the plant operation
Baghouse on exhausts	99%	Good control, proven technology	Added cost for the plant operation
Process changes			
Eliminate minus 325-mesh material in feed	100% for respirable dust	Removes respirable dust	
Wet the mixed batch	100%	Controls dust from batch charging; provides better furnace melting	

on conveying systems that use open conveyor belts. A reduction in the size of the dust control equipment can be realized by totally enclosing all conveying equipment and sealing all covers and access openings with gaskets of polyurethane foam. In fact, by totally enclosing all conveying equipment, exhaust systems become unnecessary and relatively small filter vents or dust cabinets can be attached directly to the conveying equipment and storage bins.[12]

Weigh hoppers and mixers require ventilation because of surges in material which result in large air flows. The exhaust can be satisfactorily filtered of particulates in a baghouse. Seals of polyvinylchloride should be installed between the rotating body of the mixer and its frame to reduce air leaks.

The problem of dusting has also been alleviated by severely limiting the amount of fine particles (<325-mesh) in the feed material. Experience has shown that <44 μm (minus 325-mesh) particles cause severe dusting.[12,41] Manufacturers specify that glass sand should be all <0.82 mm (minus 20-mesh) and all >44 μm (plus 325-mesh). The specifications for an acceptable glass sand appear in Table 16. The table also gives the particle sizes corresponding to given mesh sizes. Although there are no mesh requirements spelled out for the sizes less than 0.41 mm (40-mesh) nor greater than 0.105 mm (140-mesh), the distribution should be reasonably uniform on the intermediate screens.

In a similar way glass grade limestone and dolomite are processed to remove fine material. Since these materials

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[41] Brown, C. J. Selection Criteria for Sand, Dolomite, and Limestone in the Flat Glass Industry. In: Collected Papers from the 32nd Annual Conference on Glass Problems. Dept. of Ceramic Engineering, University of Illinois, Urbana, November 1971. p. 163-171.

Table 16. ACCEPTABLE MESH SPECIFICATION FOR GLASS SAND[41]

Requirement	U.S. standard mesh size	Particle size	Limits
Cum.[a] retained on	20	820 μm	0.0%
Cum. retained on	40	410 μm	12.0% Max
Cum. retained on	140	105 μm	92.0% Min
Cum. retained on	200	74 μm	99.5% Min
Cum. retained on	325	44 μm	100.0% Min

Mesh Size and Corresponding Particle Size

U.S. standard mesh size	Approximate particle size
8	2.3 mm
16	1.3 mm
20	820 μm
40	410 μm
100	150 μm
140	105 μm
200	74 μm
325	44 μm

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[a] Cum. = cumulative.

crush to dust more easily than sand they are sold as a coarser mixture. Specifications that minimize dusting are given in Tables 17 and 18. Dolomite is sold as either a 2 mm (10-mesh) stone or a 0.82 mm (20-mesh) stone.

Another process modification that controls dusting is the addition of a small amount (3%) of water to the mixed batch. The water contains a surfactant to aid in wetting the raw materials. The moisture eliminates dusting during the batch charging operation, prevents the segregation of batch ingredients, and permits the use of less salt cake in the batch.[17] Pelletizing the batch materials is another technique which accomplishes the same results.

All of these control techniques are now standard practice in the flat glass industry.

B. THE GLASS MELTING FURNACE

The major effort in controlling emissions from glass furnaces has been through process modifications rather than pollution control devices. Typical approaches include controlling raw materials to reduce the amount of volatilizable materials (e.g., sulfates, fluorides, borates), changing the furnace design and operation to give greater fuel efficiency, and increasing the checkerwork volume for better heat savings.

A number of these process changes have been made primarily to reduce the cost of glass making, but they also contribute indirectly to a reduction in air emissions. This indirect effort comes about because a decrease in fuel requirements will be accompanied by a decrease in combustion products, a decrease in dust entrainment by hot combustion gases passing over the molten gas, and in some cases by a decrease in the furnace temperature.

Table 17. ACCEPTABLE MESH SPECIFICATION FOR GLASS GRADE DOLOMITE[41]

Requirement	U.S. standard mesh size	Particle size	Limits 2 mm (10-mesh)	 0.82 mm (20-mesh)
Cum.[a] retained on	8	2.3 mm	0.0%	0.0%
Cum. retained on	16	1.3 mm	15.0% Max	
Cum. retained on	20	820 μm		2.0% Max
Cum. retained on	100	150 μm	90.0% Min	80.0% Min
Cum. retained on	140	105 μm		95.0% Min
Cum. retained on	200	74 μm	97.0% Min	96.0% Min

[a] Cum. = cumulative.

Table 18. ACCEPTABLE MESH SPECIFICATION FOR GLASS GRADE LIMESTONE[41]

Requirement	U.S. standard mesh size	Particle size	Limits
Cum.[a] retained on	8	2.3 mm	0.0%
Cum. retained on	16	1.3 mm	2.0% Max
Cum. retained on	20	820 μm	10.0% Max
Cum. retained on	140	105 μm	85.0% Min
Cum. retained on	200	74 μm	94.0% Min

[a] Cum. = cumulative.

In the same way factors that increase furnace life will decrease emissions by improving the operating efficiency. Better refractories are a case in point, both in the furnace and in the checkerworks. An eroded and partially plugged checkerwork loses efficiency as a heat regenerator.

Unfortunately it is not possible to quantify the effects of specific process changes in lowering emission rates because a number of variables in the furnace operation are usually changed simultaneously. As an example, supplemental electric heating will, in itself, result in a lower furnace temperature and lower particulate emissions. However, the production rate is generally increased at the same time so that the furnace temperature remains the same.

Another factor which should be noted is the continual improvement in furnace operations. The 1970-1972 data from which the emission factors in Section IV were determined do not reflect the actual performance in 1975. Nor would 1975 data give a true picture of 1978.

1. Process Modification

The effects of process modifications can best be discussed in terms of specific air emissions. Particulates, for instance, are generated by the entrainment of dust in combustion gases and by the volatilization of materials in the melt. The elimination of <44 μm (minus 325-mesh) particles in the feed material and the addition of water to the glass batch, as discussed in Section V.A, will minimize dust entrainment.

Volatilization of the melt can be reduced by controlling the feed material, by proper furnace design, by lowering the furnace temperature, and by electric melting.[12,42] Raw materials which vaporize in the melt include sulfates, borates, nitrates, fluorides, chlorides, arsenic, selenium, antimony, and lead. Of these only sodium sulfate is still used as a standard ingredient in flat glass. None of the others is used by more than 10% of the industry. Sodium sulfate (salt cake) or another sulfate is a necessary flux that prevents scum formation in the melting furnace and aids in the melting process. Manufacturers reduce the salt cake in the glass batch as much as possible consistent with good glass making. Exact details are considered proprietary.

Emissions from fluxing agents can be lowered by improving overall furnace efficiency. The following methods that improve this efficiency are being practiced:[12,43]

- Applied instrumentation to regulate air/fuel mixtures, monitor furnace temperature and stack gas composition, automatically charge the batch into the furnace, and reverse the air flow through the regenerative checkers.
- Combustion control to produce large luminous flames that eliminate hot spots in the furnace and provide better heat transfer to the melt.
- Increased checker volume for better heat recovery (the ratio of checker volume to melter area is about 2.74 m^3/m^2 today).
- Improved refractories for corrosion resistance and better insulation.

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[42] Simon, H., and J. E. Williamson. Control of Fine Particulates from Continuous Melting Regenerative Container Glass Furnaces. Los Angeles County Air Pollution Control District. (Presented at the 68th Annual Meeting of the Air Pollution Control Association. Boston. June 15-20, 1975.) 12 p.

[43] Hamilton, J. C. Applied Research in Glass Melting. Industrial and Engineering Chemistry. 52:16-21, February 1970.

As a result of these measures the average amount of fuel needed to melt a metric ton of glass decreased from about 10.5 GJ in 1936 to 7.1 GJ in 1964 (theoretical amount is 1.9 GJ/metric ton).[9,42]

The increased checker volumes not only reduce fuel consumption but also present a trap for dust particles. Although dust collects within checkers by the mechanisms of impingement and settling (gaseous materials also condense out on the checkers), the relationship among various factors influencing collection is unknown. These factors include gas velocity and temperature, brick size and composition, flue spacing, and brick setting. It is known that micron-size particles are trapped in the checkers while submicron-size particles escape and go out the stack (see Section IV).[12,25]

As mentioned in Section IV the furnace temperature has a profound influence on the particulate emission rate. Two studies have found the emissions rate to increase exponentially with temperature.[24,34] The furnace temperature can be lowered by improving furnace efficiencies, by decreasing the production rate, and by using supplemental electric heating.

Glass conducts electricity at high temperatures and it can be melted by passing an electric current through it.[9] The use of electrical energy to assist in a fuel-fired furnace is called electrical boosting. Although boosting is not practiced in flat glass furnaces, it is widespread in the container glass industry. Boosting permits a furnace to operate at a lower temperature with the same production rate because heat is being introduced near the bottom of the molten glass as well as at the surface.[42] (All-electric furnaces are available, but they are unsuited for the large-scale flat glass production.)

The results of all these process changes are illustrated by two glass container furnaces in California that used the options outlined above to meet state and county (Los Angeles) emission standards. They were tested 13 times from 1972 to 1975 and had an average particulate emission factor of 0.29 ± 0.048 g/kg (vs. 1 g/kg for the industry average in Table 8). However, three other furnaces were unable to meet the regulations by these means and pollution control equipment had to be installed.[42]

All the methods discussed for reducing volatilization can also be used to control gaseous emissions. Sulfur oxides are formed from sulfates that decompose in the melt, and they can be controlled by limiting the amount of sulfate in the feed material and by improving the furnace efficiency. One study found that the SO_x emission rate increased directly with an increase in production rate on a furnace melting soda-lime glass.[24] The authors stated that the increase was a result of higher furnace temperatures (1,552°C vs. 1,460°C) at the increased production rate (180 metric tons/day vs. 90 metric tons/day).

A fuel oil containing 1% sulfur produces about 600 ppm SO_x in the flue gas.[31] In such a case a change from oil to natural gas will lower emissions, but this is no longer a viable option with the deteriorating natural gas supply. Natural gas firing is preferred by glass producers since it causes less wear on the furnace refractories.

Nitrogen oxides form in the melting furnace by a combination of atmospheric oxygen and nitrogen. Emission levels can be lowered by increasing the furnace efficiency and decreasing the furnace temperature. Other factors being equal, a 10% decrease in fuel consumption should be reflected in a 10% decrease in NO_x emissions.

The reaction between N_2 and O_2 is strongly temperature dependent (see Table 19), so that careful control of combustion and elimination of hot spots in the furnace will reduce the formation of NO_x.[29] Doubling the production rate from 90 to 180 metric tons/day (which was accompanied by a higher furnace temperature, 1,460°C to 1,552°C) resulted in a sixfold increase in the NO_x emission rate (from 100 ppm to 600 ppm).[24]

Table 19. TIME FOR NO FORMATION IN A GAS CONTAINING 75% NITROGEN AND 3% OXYGEN[29]

Temperature, °C[a]	Time to form 500 ppm NO, s[b]	NO concentration at equilibrium, ppm
1,360	1,370	550
1,538	16.2	1,380
1,760	1.10	2,600
1,982	0.117	4,150

[a] The glass melt temperature is ∿1,500°C.

[b] A large (500 metric tons/day) furnace would have an air flow of ∿94 m^3/s and an air space in the furnace of ∿2,830 m^3, for a residence time of ∿30 s.

2. Pollution Control Devices

Add-on control devices have not been used on flat glass furnaces because process modifications are able to meet state and federal emission standards. The only problem area is opacity regulations which may be exceeded because of the submicron size of the particulates.

Other sections of the glass industry, particularly the Glass Container Manufacturers Institute, have studied the applicability of different controls to particulate collection. Problems encountered in adapting equipment to glass furnace exhausts include the submicron particle size, the corrosive nature of exhaust gases, and high stack gas temperatures (sometimes over 550° C). Systems that have undergone testing are scrubbers, baghouses, electrostatic precipitators, and two new methods proposed by Teller Environmental Systems, Incorporated (TESI).[12,44-50]

a. Scrubbers - A low-pressure, wet, centrifugal scrubber that was used by the Thatcher Glass Co. in Saugus, California, showed an overall particulate collection efficiency of 52%.[12] The low efficiency demonstrates the inherent inability of such scrubbers to collect particulates of submicron size.

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[44] Edmondson, J. N., L. Reitz, R. L. Weise, and J. Fraas. Design, Installation, and Operation of Equipment to Cool and Filter Particulate Matter from Flue Gas from a Regenerative Furnace. In: Collected Papers from the 32nd Annual Conference on Glass Problems. Dept. of Ceramic Engineering, University of Illinois, Urbana, November 1971. p. 39-54.

[45] Teller, A. J. Control of Emissions from Glass Manufacture. Ceramic Bulletin. 51:637-640, August 1972.

[46] Frantz, C. N., D. L. Miser, H. N. Troy, and E. D. Stobbe. Glass Furnace Particulate Emission Control Equipment. In: Collected Papers from the 32nd Annual Conference on Glass Problems. Dept. of Ceramic Engineering, University of Illinois, Urbana, November 1971. p. 25-38.

[47] Keller, G. Scrubber System Lightens Load of Glass Furnace Emissions. Chemical Processing. 38:9, January 1975.

[48] Symposium on Pollution, Stratford-Upon-Avon, 30 May - 1 June, 1973. In: Glass Technology. 14(6):140-144, December 1973.

[49] Tank Emissions "Bagged." The Glass Industry. 55:18, July 1974.

[50] Moyer, T., S. Reigel, and C. Doyle. Gas-Assisted Atomizers Help End High Heat Problem in Collector. Maintenance Engineering. 22:28-29, June 1972.

Owens-Illinois tested an adjustable throat, high-energy venturi scrubber with a system that collects and recycles the scrubbing liquor back to the venturi throat. Although the scrubber performed adequately (collection efficiencies of 85% to 95% and stack gas effluent within state standards), the cost of a water treatment system for the scrubber liquor blowdown was excessive.[46] (Owens-Illinois did not report actual cost data.)

The FMC Corporation has developed a new scrubber with a packed bed preconditioning chamber. Hot gases (540°C) containing volatilized sodium compounds enter the chamber and the vapors condense out on the packing material. This material, which is wet by the scrubbing solution, provides a large surface area for condensation. A standard venturi type scrubber completes the system. The scrubber is installed on a 150 metric ton/day container glass furnace in Vernon, California, and reduces the particulate loading by ∿70%. Thus far the system has suffered from many malfunctions and breakdowns.[42,47]

b. Fabric Filters - At least four different fabric filters have been used in baghouses to control glass furnace particulate emissions (Nomex, Dacron, Teflon, and fiber glass).[12,42,44,46,48-50] Owens-Illinois conducted a feasibility study in 1969 using Nomex bags on a borosilicate glass furnace. The collection efficiency was greater than 99%, but serious fabric plugging occurred with attendant high pressure losses when the outlet gas temperature dropped much below 150°C in the pilot unit, probably due to condensation on the colder bags.[46] Nomex was also used successfully on a multifurnace plant operated by General Electric.[44] Some problems were encountered when the bags came apart at the seams, perhaps because the stitching was abraded by the dust.

Owens-Illinois also tested a Teflon bag filter that had a life of 15 months.[48] No operating data were reported.

Dacron filter bags were used on a 130 metric ton/day container glass furnace in Los Angeles. Particulate collection efficiencies ranged from 64% to 82% while the opacity reading was 0%.

Glass fiber bags have been used on several furnaces but their lifetimes were only mentioned once.[12,49,50] One baghouse operating at 205°C alternately vents two small (820-kg and 2,300-kg) regenerative furnaces.[12] Another operates on a 180-metric ton furnace in which exhaust gas at 650°C is cooled by a water spray to ∿260°C.[13,50] A collection efficiency of 99+% was reported, but subsequent tests indicated that some of the volatilized particulates were not collected because of the high baghouse temperature. The addition of cooling air made the filtering velocity too high for sustained use. A third system utilized four collectors at 250°C. Only one bag failed in 18 months of test operations.[49]

Temperature control is very critical for the proper functioning of a baghouse. Since the stack gas from a glass furnace is at 350°C to 650°C, the gas must be cooled to a temperature compatible with the bag material. Maximum operating temperatures for some typical fabric filters are given in Table 20.[44]

Temperatures must also be controlled at the low end since SO_3 and H_2O in the gas stream can condense and foul the bags.[12] The furnace effluent can be cooled by several methods, either alone or in combination.[12,44] These methods are: (1) air dilution, (2) radiation cooling columns, (3) air-gas heat exchangers, and (4) water spray chambers.

Table 20. MAXIMUM USE TEMPERATURE FOR FABRIC FILTERS[44]

Fabric	Maximum temperature, °C
Cotton sateen	88
Standard nylon	93
Wool	107
Dacron	135
Orlon	135
Nomex	204
Teflon	232
Fiber glass	288

Each cooling method has its advantages and disadvantages. Dilution of off-gases with air is the simplest and most troublefree way to reduce temperature but requires the largest baghouse. Air-to-gas heat exchangers and radiation and convection ductwork are subject to rapid fouling from dust in the effluent. A water spray increases the humidity and requires careful temperature control to avoid condensation, but it does permit the use of a smaller baghouse.

The fabrics used in the baghouse must be chosen not only for their heat resistance but also for their resistance to corrosion and abrasion. Experience has shown that cotton, Orlon, and Dacron are deteriorated by SO_3 in the flue gas.[12] It is likely that nylon and wool would also be attacked by acidic gases.

c. Electrostatic Precipitators - Tests with electrostatic precipitators have shown that their collection efficiency is from 80% to 98% for particulates from glass melting furnaces.[42,46,48,a] Owens-Illinois conducted a pilot-scale study on a borosilicate furnace and achieved between 40% and 95% efficiency. A full-scale unit operated at 80% to 90% efficiency. Factors that prevented better performance were the size and resistivity of the particles and the plate cleaning procedures. Operating temperature of the full-scale unit was ∿370°C and it was felt that a hotter operating temperature (430°C), which would reduce the particle resistivity by a factor of 10, should improve the collection efficiency.[46]

Another electrostatic precipitator was reported to achieve 80% removal only with difficulty, even though it was working well within capacity.[48]

An electrostatic precipitator is installed on a glass container furnace in California (∿180 metric tons/day capacity). The two-chamber unit has an efficiency of 83% to 89% and functions with equal efficiency whether one or two chambers are used.[42]

The Japanese firm of NAFCO Engineering, Ltd., has developed an entirely new type of electrostatic precipitator. It was designed to clean dust emissions from glass furnaces to meet Japanese emission standards. In contrast to conventional units in which hanging wires discharge electricity, the NAFCO ESP (electrostatic precipitator) uses thousands of stainless steel needles affixed to the leading and trailing edges of positively charged electrode plates. The Japanese have some 35 systems in operation, 60% on lead glass furnaces, 15% on borosilicate glass, and 25% on soda-lime glass.[36]

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[a] An efficiency of 98% was reported by a flat glass manufacturer on a pilot-scale unit.

The licensed U.S. distributor, United McGill Corporation, has installed the new ESP on 12 glass furnaces (five borosilicate glass, four lead glass, three soda-lime glass), and 30 units are scheduled to be in operation by mid-1975 (10 borosilicate glass, 10 lead glass, 10 soda-lime glass). All of the systems in operation have an efficiency of at least 85%, based on a minimum uncontrolled emission factor of 1 g/kg glass and an air flow of 3 m^3/kg glass. The Japanese ESP is designed so that additional sections can be added to attain higher efficiencies (stated to be >99%) if desired.[36]

d. TESI - Teller Environmental Systems, Inc., (TESI) offers a dry and a wet system for emissions control. The wet system uses a nucleation scrubber to effect collection of submicron particulates and acid gases (SO_x). In the dry system a solid absorbent is injected into the gas stream to react with noxious gases. The absorbent is separated from the gas along with the particulates in a fabric filter. Pilot-scale studies on a slipstream (180 m^3/min) from a fiber glass furnace showed collection efficiencies of 96% for particulate and 99% for SO_x.[45] An attempt to use the system on a flat glass furnace failed because of engineering problems.

e. Summary - Table 21 summarizes the advantages and disadvantages of the different control techniques. Although baghouses and electrostatic precipitators remove only particulates, it has been suggested that spraying the stack gas with an alkaline solution would cause acid gases (SO_x) to react and form particulates.[36] These could then be collected by the control device.

Control development has focused on particulate removal to meet emission standards for stack opacity. As a result, there is no proven technology for NO_x removal from stack gases, and the effect on NO_x emission levels by process

Table 21. CONTROL TECHNIQUES FOR GLASS MELTING FURNACES

Control	Emission controlled	Efficiency	Advantages	Disadvantages
Process modifications				
Remove volatile materials from batch	Borates Fluorides Arsenic Selenium Chlorides	100% 100% 100% 100% 100%	Most economical, complete control	May affect glass quality
Remove minus 325-mesh materials; wet the mixed batch	Particulates	Primarily controls dust carried into checkerwork rather than stack emissions	Controls dust entrainment; stops segregation of raw materials	
Reduce sulfate in batch	Particulates SO_x	Depends on % sulfate reduction	Inexpensive way to reduce particulates and SO_x	Careful operation is required to maintain glass quality
Improve furnace efficiency	Particulates SO_x NO_x CO_x Hydrocarbons	Function of furnace efficiency	Actually saves money	Even at 100% energy utilization there are still emissions
Electrical boosting	Particulates SO_x NO_x CO_x Hydrocarbons	Dependent on the amount of boosting	Reduces all emissions at same production rate	Not developed for flat glass

Table 21 (continued). CONTROL TECHNIQUES FOR GLASS MELTING FURNACES

Control	Emission controlled	Efficiency	Advantages	Disadvantages
Control devices				
Scrubbers	Particulates SO_x NO_x	Up to 95% Up to 90% Unknown	Controls both particulate and SO_x	Low efficiency for submicron particulates; high energy requirement; wastewater
Fabric filters	Particulates	Up to 99%	Good particulate control	Only controls particulates; temperature control is critical, fabric corrosion
Conventional ESP	Particulates	Up to 98%	Good particulate control	Only controls particulates
Japanese ESP	Particulates	Up to 99%	Good control; proven technology	Only controls particulates
TESI	Particulates SO_x NO_x	96% 99% Unknown	Controls both particulate and SO_x	System has failed to operate on more than a pilot scale

modifications is unknown. The wide variation in reported NO_x emission factors (Table C-4 in Appendix C) suggests a best case condition of 1 g/kg (vs. an average of 4 g/kg). However, it is doubtful whether other furnaces could reach this level without lowering their production level.

C. FORMING AND FINISHING OPERATIONS

Because atmospheric emissions from these operations are low (<0.1 g/kg) or nonexistent, control devices are unnecessary. Annealing lehrs of increased efficiency do produce fewer combustion products per metric ton of glass annealed, but that is not why they are used. Rather, they are desirable because they consume less energy. The new recirculating air type lehrs can save 40% to 60% of the fuel cost over the older, nonrecirculating models.[27,28]

SECTION VI

GROWTH AND NATURE OF THE FLAT GLASS INDUSTRY

The past 10 years have witnessed a revolution in the flat glass industry as the float process has displaced the older plate glass process and even made inroads on sheet glass production. There is presently only one plate glass plant still in operation and two sheet glass plants have been shut down. Future trends in the industry will see sheet glass being replaced by thin float glass.[22,26,51]

The production statistics in Table 22 indicate that float production in 1973 was more than twice the 1967 level of float and plate, while sheet production remained constant. Since plate glass weighs twice as much as sheet glass, the overall increase was 81%, or about 10% per year. In 1974 the slump in the economy caused a slight decline in production. If growth resumes in 1975, the 1978 production level will be 46% above that for 1973. Total national emissions will also increase by this amount unless there are new developments in control technology.

Other development trends in the flat glass industry include the increasing use of automation[15,21,51] and a new, more

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[51] Child, F. S. The Impact of Flat Glass Imports. The Glass Industry. 52:166-169, May 1971.

Table 22. FLAT GLASS PRODUCTION STATISTICS[2,52]

Year	Sheet glass production, km^2	Plate, float, rolled and wire glass production, km^2 (only 5% is rolled and wire glass)
1974	92.4	170.8
1973	110.1	173.4
1972	117.5	141.4
1967	101.7	77.2

efficient design for annealing lehrs. The new lehrs are expected to replace the older nonrecirculating type lehrs.[27] New techniques are also available for making tinted and reflective glass for architectural applications.

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[52] Ceramic Industry Newsletter. Ceramic Industry. 104:9, May 1975.

SECTION VII

UNUSUAL RESULTS

Along with many other industries the flat glass industry is experiencing a natural gas shortage. This has a direct effect on air emissions because the oil that is used as a fuel substitute contains sulfur. As a general guideline, a changeover from gas to oil will double the emission factors for SO_x and particulates.

A factor tending to counter this effect is the improved furnace efficiency being achieved by process modifications that act to reduce stack emissions. There is no way to predict the quantitative impact of these two factors on future air emissions.

SECTION VIII

APPENDIXES

A. Calculation of Glass Production on a Tonnage Basis
B. Flat Glass Plant Listing
C. Emissions Data
D. Total Flat Glass Emissions
E. Plume Rise Correction
F. Derivation of Source Severity Equations

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APPENDIX A

CALCULATION OF GLASS PRODUCTION ON A TONNAGE BASIS

The production of glass products is not reported on a tonnage basis; instead the statistics list square feet of flat glass or number of glass containers. Consequently the U.S. production was estimated from the amount of raw materials consumed in each category in 1972.[2-4]

1. FLAT GLASS

Raw materials consumed in 1972	metric tons	(tons)
Sodium carbonate	494,000	(544,500)
Glass sand	1,840,000	(2,028,000)
Sodium sulfate	60,000	(66,700)
Cullet (glass scrap)	374,000	(412,450)

The total weight of these raw materials is 2.768×10^6 metric tons (3,051,650 tons). Two facts should be noted: (1) a number of raw materials (e.g., lime) are not listed individually (the total cost for all other materials is reported instead); and (2) sodium carbonate and lime decompose in the glass furnace and give off CO_2. The consumption of lime can be estimated since it muast be approximately equal to the consumption of sodium carbonate to give the proper batch composition, i.e., 4.94×10^5 metric tons (544,500 tons).

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Data from the Bureau of Mines indicate that consumption of aluminum-bearing minerals (feldspar, aplite, and nepheline syenite) in the glass industry was about 9.10×10^5 metric tons (1 million tons) in 1972.[53] This has been broken down as follows: 9.1×10^4 metric tons (100,000 tons) in flat glass, 2.73×10^5 metric tons (300,000 tons) in pressed and blown glass, and 5.44×10^5 metric tons (600,000 tons) in glass containers. The low value for flat glass reflects the fact that these materials are not used in float glass production.

The total weight of these ingredients is 3.353×10^6 metric tons (3,696,150 tons). After the decomposition of sodium carbonate and limestone to give off CO_2 and sodium sulfate to give off SO_3 there will be a weight loss of 4.56×10^5 metric tons (503,200 tons). The final production is then 2.9×10^6 metric tons (3.2 million tons), which compares favorably with a 1972 transportation survey showing flat glass shipments of 2.8×10^6 metric tons (3.1 million tons).[54]

As noted previously, there is a high (30% to 50%) ratio of cullet used in the glass batch. The quantity given in the data (11%) represents only purchased cullet material, not off-quality and broken glass that is recycled. Therefore the amount of glass which is actually made is higher than reported or approximately 4×10^6 metric tons (4.4 million tons). Finally, the total amount of raw materials handled (taking into account volatilization losses) is 4.5×10^6 metric tons (4.9 million tons). The accuracy of these numbers is on the order of ±10% because of the variation in the cullet ratio. These figures are summarized below:

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[53] Wells, J. R. Feldspar, Nepheline Syenite, and Aplite. In: Minerals Yearbook 1972, Volume I: Metals, Minerals and Fuels. Bureau of Mines, Washington. 1974. p. 515-523.

[54] Ceramic Industry Newsletter. Ceramic Industry. 104:7, February 1975.

Flat Glass - 1972	10^6 metric tons/year	(tons/year)
Finished products	2.9	(3.2 million)
Total flat glass made	4.0	(4.4 million)
Raw materials handled	4.5	(4.9 million)

For comparison the current (mid-1975) flat glass capacity is ∿14,290 metric tons/day. An 80% capacity for a full year would give a production level of 4.2 x 10^6 metric tons (4.6 million tons).

2. GLASS CONTAINERS

Raw materials consumed in 1972	metric tons	(tons)
Sodium carbonate	2,380,000	(2,617,800)
Glass sand	7,379,000	(8,116,300)
Cullet	1,459,000	(1,604,800)
Aluminum-bearing minerals (est.)	545,000	(600,000)

The flat glass calculations show that the amount of lime is close (8%) to the volatilization loss. With this assumption the estimated production of glass containers would be 11.7 x 10^6 metric tons (12,938,900 tons). This compares well with the reported "net weight of machine-made glass containers packed" of 11.5 x 10^6 metric tons (12,663,950 tons).[3]

3. PRESSED AND BLOWN GLASS, N.E.C.

Raw materials consumed in 1972	metric tons	(tons)
Sodium carbonate	230,000	(252,500)
Glass sand	3,309,000	(3,639,400)
Cullet	350,000	(385,350)
Aluminum-bearing minerals (est.)	273,000	(300,000)

Estimated production of finished products is 4.062×10^6 metric tons (4,477,250 tons), or $\sim 4.1 \times 10^6$ metric tons ($\sim$4.5 million tons).

4. TOTAL PRODUCTION

The total production of finished glass products is then 1.86×10^7 metric tons.

APPENDIX B

FLAT GLASS PLANT LISTING

Flat glass plants are listed in Table B-1 by state. Data presented are plant capacities, number of melting furnaces (designated "tanks"), location by city and county, county population density, and AQCR. Plant capacities are based on data in References 6, 7, 14 and 26 and communications with industry representatives. Actual capacities were not always known and had to be estimated from production data.

2 OF 2

PB

252 356

1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

Table B-1. LISTING OF FLAT GLASS PLANTS

Plant	Product	Location				County population density, persons/km^2 (persons/mi^2)	Furnaces and capacities
		State	City	County	AQCR		
Fourco Glass Co.	Sheet	Arkansas	Fort Smith	Sebastion	17	57 (147)	2 tanks; 200 metric tons (225 tons)
C.E. Glass, Inc.	Rolled	California	Fullerton	Orange	24	696 (1802)	1 tank; 64 metric tons (70 tons)
Libbey-Owens-Ford	Float	California	Lathrop	San Joaquin	31	78 (201)	1 tank; ∼400 metric tons (∼450 tons)
PPG Industries	Sheet	California	Fresno	Fresno	31	26 (68)	1 tank; ∼360 metric tons (∼400 tons)
Libbey-Owens-Ford	Float	Illinois	Ottawa	LaSalle	71	37 (96)	1 tank; ∼360 metric tons (∼400 tons)
PPG Industries	Sheet	Illinois	Mt. Zion	Macon	75	83 (215)	1 tank; ∼400 metric tons (∼450 tons)
PPG Industries	Float	Maryland	Cumberland	Allegany	113	74 (192)	1 tank; ∼360 metric tons (∼400 tons)
Ford Motor Co.	Float	Michigan	Dearborn	Wayne	123	1792 (4638)	1 tank; ∼360 metric tons (∼400 tons)
Guardian Ind. Corp.	Float	Michigan	Carleton	Monroe	124	82 (211)	2 tanks; 820 metric tons (900 tons)
C.E. Glass, Inc.	Rolled	Missouri	St. Louis	(Independent City)	70	1083[a] (2803)	2 tanks; 177 metric tons (195 tons)
PPG Industries	Float	Missouri	Crystal City	Jefferson	70	59 (153)	1 tank; ∼360 metric tons (∼400 tons)
C.E. Glass, Inc. (new plant)	Float	New Jersey	Cinnaminson	Burlington	45	153 (396)	1 tank; ∼450 metric tons (∼500 tons)
Libbey-Owens-Ford	Float	North Carolina	Laurinburg	Scotland	169	32 (83)	1 tank; ∼680 metric tons (∼750 tons)
Libbey-Owens-Ford	Float	Ohio	Rossford	Wood	124	55 (144)	2 tanks; ∼900 metric tons (∼1000 tons)
Libbey-Owens-Ford	Float	Ohio	Toledo	Lucas	124	539 (1396)	1 tank; ∼400 metric tons (∼450 tons)

[a] Population density is for the city of St. Louis plus the surrounding county of St. Louis.

Table B-1 (Continued). LISTING OF FLAT GLASS PLANTS

Plant	Product	Location				County population density, persons/km^2 (persons/mi^2)	Furnaces and capacities
		State	City	County	AQCR		
PPG Industries	Sheet	Ohio	Mt. Vernon	Knox	175	31 (79)	3 tanks; ∿600 metric tons (∿660 tons)
ASG Industries	Sheet	Oklahoma	Okmulgee	Okmulgee	186	19 (49)	2 tanks; 160 metric tons (180 tons)
Ford Motor Co. (new plant)	Float	Oklahoma	Tulsa	Tulsa	186	268 (694)	2 tanks; ∿900 metric tons (∿1000 tons)
ASG Industries	Sheet	Pennsylvania	Jeanette	Westmoreland	197	142 (369)	1 tank; 245 metric tons (270 tons)
C.E. Glass, Inc.	Float	Pennsylvania	Floreffe	Allegheny	197	842 (2180)	1 tank; ∿360 metric tons (∿400 tons)
PPG Industries	Float	Pennsylvania	Carlisle	Cumberland	196	109 (283)	2 tanks; ∿900 metric tons (∿1000 tons)
PPG Industries	Float	Pennsylvania	Meadville	Crawford	178	30 (77)	2 tanks; ∿730 metric tons (∿800 tons)
ASG Industries	Float[b]	Tennessee	Greenland	Sullivan	207	116 (301)	2 tanks; ∿720 metric tons (800 tons)
ASG Industries	Rolled	Tennessee	Kingsport	Sullivan	207	116 (301)	5 tanks; 295 metric tons (325 tons)
C.E. Glass, Inc.	Rolled	Tennessee	Erwin	Unicol	207	31 (81)	1 tank; ∿64 metric tons (∿70 tons)
Ford Motor Co.	Float	Tennessee	Nashville	Davidson	208	402 (1041)	3 tanks; ∿1360 metric tons (∿1500 tons)
PPG Industries (new plant)	Float	Texas	Wichita Falls	Wichita	210	75 (194)	2 tanks; ∿900 metric tons (∿1000 tons)
Fourco Glass	Sheet	West Virginia	Clarksburg	Harrison	235	66 (171)	2 tanks; 180 metric tons (200 tons)
Libbey-Owens-Ford	Sheet	West Virginia	Charleston	Kanawha	234	95 (247)	2 tanks; ∿360 metric tons (∿400 tons)

[b] 1 float, 1 polished plate (color only).

APPENDIX C

EMISSIONS DATA

1. RAW MATERIALS PREPARATION

The preparation of raw materials has been divided into five operations: (1) handling of raw materials (unloading, conveying); (2) crushing of scrap glass; (3) filling and emptying storage bins; (4) batch mixing (and weighing); and (5) feeding of mixed glass batch to melting furnace (batch charger). Source test data are summarized in Table C-1; additional data based on material balances and engineering estimates appear in Table C-2. The data base includes not only flat glass plants but container glass and pressed and blown glass. Since the preparation of raw materials is the same for all three categories, this provides a broader base.

As mentioned in the text, emissions from handling and batch charging were estimated to be zero based on observation at a large float glass plant. The low level of emissions from other points was also confirmed since there were no visible particulate emissions from the batch house.

The average emission factor for batch mixing, based on the six source test measurements, is 1.58 mg/kg ± 106% at a 95% confidence level. For raw materials storage it is 12.3 mg/kg, based on one source test and seven engineering

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Table C-1. SUMMARY OF SOURCE TEST DATA FROM NEDS - MATERIALS HANDLING AND MIXING[14]

Plant	Material processed, metric tons/yr (tons/year)	Particulate emissions, metric tons/yr (tons/year)	Emission factor, mg/kg (lb/ton)	Control equipment	Process
X	258,000 (284,000)	0.9 (1)	3.5 (0.007)	Fabric filter	Batch mixing
B	755,000 (830,000)	3.6 (4)	5 (0.010)	Fabric filter	Raw material handling and storage
R	46,000 (50,600)	0 (0)	0 (0)	Wet scrubber	Batch mixing
W	277,000 (305,000)	0.9 (1)	3 (0.006)	Fabric filter	Batch mixing
	135,000 (148,000)	0 (0)	0 (0)	Fabric filter	Batch mixing
	277,000 (305,000)	0 (0)	0 (0)	Fabric filter	Batch mixing
MM	291,000 (320,000)	0.9 (1)	3 (0.006)	None listed	Batch mixing

Table C-2. PARTICULATE EMISSIONS FROM THE PREPARATION OF RAW MATERIALS[14]
(Based on material balance and engineering knowledge)

Plant	Material processed, metric tons/yr (tons/yr)	Emissions, metric tons/year (tons/yr)	Emission factor, mg/kg (lb/ton)	Control type	Operation
R	46,000 (50,600)	0 (0) (5 points)	0 (0)	Fabric filter	Batch mix - cullet
SS	88,000 (96,800)	0.9 (1)	10.5 (0.021)	Fabric filter	Batch house
SS	122,000 (134,000)	0 (0)	0 (0)	Fabric filter	Batch house sand
SS	232,000 (255,000)	0.9 (1)	4 (0.008)	Fabric filter	Batch mixing
SS	232,000 (255,000)	4.5 (5)	20 (0.039)	Fabric filter	Batch delivery
TT	165,000 (182,000	3.6 (4)	22 (0.044)	Fabric filter	Batch silo conveyors
LL	515,000 (567,000)	12.7 (14)	25 (0.049)	Fabric filter	Raw material Receiving and storage
LL	158,000 (174,000)	9.1 (10)	55 (0.11)	Centrifugal collector	Glass crush
W	57,000 (63,000)	0.9 (1)	16 (0.032)	Fabric filter	Lime silo filtering
W	12,800 (14,100)	0 (0)	0 (0)	Fabric filter	Slag silo filtering

estimates. Only one value was reported for glass crushing (55 mg/kg), for a crusher equipped with a centrifugal collector instead of a baghouse for dust control. Since the typical control practice is a baghouse, it was decided to use the same value for the crusher as for raw materials storage (i.e., 12.3 mg/kg).

The accuracy was found by using the t-test for source test data. Thus with batch mixing the sample mean, $\overline{y}$, was 1.58 mg/kg and the sample standard deviation, s, was 1.59. The confidence limits on $\overline{y}$ are then $\pm ks/\sqrt{n}$ where k is the "Student's t" variable for n-1 degrees of freedom ($t = 2.571$), and n is the number of samples. The accuracy of the engineering estimates was assumed to be ±100%.

Stack heights for the various operations are listed in Table C-3. They range from 1.5 m (5 ft) to 44.2 m (145 ft). Since all the emissions are particulates an overall average stack height of 21.5 m (70.6 ft) and a total emission factor of 0.02 g/kg were used to calculate $\overline{\chi}_{max}$ and S. The value of S is 0.02 while $\overline{\chi}_{max}$ equals 5.0 $\mu g/m^3$.

2. GLASS MELTING FURNACE

a. Nitrogen Oxides

Source test measurements of NO_x emissions as reported in NEDS are tabulated in Table C-4. Emission factors vary from 0.71 to 10.05 g/kg (1.42 to 20.1 lb/ton), and reflect the different operating conditions (especially temperature) found in glass furnaces. The average emission factor of 3.94 g/kg (7.88 lb/ton) was found by dividing the total emissions by total production. Another average can be found by adding the emission rates together and dividing by the number of values. This value is 4.37 g/kg (8.37 lb/ton),

Table C-3. STACK HEIGHTS[14]
(ft)

Batch mixing	Storage	Glass crushing
15	72	62
15	72	
15	40	
120	120	
16	120	
5	120	
80	75	
117	145	
75		
43		
80		
75		
Ave = 54.7	Ave = 95.5	Ave = 62

Overall average = 70.6 ft or 21.5 m

indicating that small furnaces have higher emission factors. However, the difference is not significant because the standard deviation is ±3 g/kg (±6 lb/ton), and the 95% confidence limit is 1.2 g/kg (2.4 lb/ton). In addition, the individual measurements are accurate to only ±25%. An average emission factor of 4 g/kg (8 lb/ton) is used in the main report.

b. Sulfur Oxides

Source test data are presented in Table C-5. Emission factors vary from 0.20 to 4.43 g/kg (0.41 to 8.85 lb/ton), with a number average of 1.35 g/kg (2.71 lb/ton) and a weight average of 1.62 g/kg (3.23 lb/ton). Since the standard

Table C-4. NO_x EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production, metric tons/year (tons/year)	Emissions, metric tons/yr (tons/year)	Emission factor, g/kg (lb/ton)	Product
A	46,200 (50,800)	51 (56)	1.1 (2.20)	Glass containers (one stack, two furnaces)
C	32,000 (35,100)	168 (185)	5.3 (10.5)	Glass containers
C	11,800 (13,000)	63 (69)	5.3 (10.6)	Glass containers
C	34,800 (38,300)	185 (203)	5.3 (10.6)	Glass containers
C	48,000 (52,700)	254 (279)	5.3 (10.6)	Glass containers
D	143,000 (157,000)	1,490 (1,640)	10.5 (20.9)	Flat glass
E	36,600 (40,300)	227 (250)	6.2 (12.4)	Glass containers
E	41,400 (45,500)	118 (130)	2.85 (5.71)	Glass containers
E	99,100 (109,000)	382 (420)	3.85 (7.71)	Glass containers
F	85,800 (44,100)	52 (57)	1.3 (2.59)	Glass containers
F	47,700 (52,500)	300 (330)	6.3 (12.6)	Glass containers
G	56,000 (62,000)	152 (167)	2.7 (5.39)	Glass containers
H	39,700 (43,700)	222 (244)	5.6 (11.2)	Glass containers
H	34,000 (37,400)	295 (325)	8.7 (17.4)	Glass containers
H	39,000 (42,900)	393 (432)	10.5 (20.1)	Glass containers
I	70,300 (77,300)	350 (385)	5.0 (9.96)	Glass containers (two furnaces)

Table C-4 (continued). NO_x EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production, metric tons/year (tons/year)	Emissions, metric tons/yr (tons/year)	Emission factor, g/kg (lb/ton)	Product
K	27,500 (30,300)	27.3 (30)	0.99 (1.98)	Glass containers
K	34,800 (38,300)	49.5 (55)	1.44 (2.87)	Glass containers
K	71,200 (78,300)	78 (86)	1.1 (2.2)	Glass containers
P	179,000 (197,000)	735 (809)	4.11 (8.21)	Glass containers (five furnaces)
S	58,800 (64,700)	51 (56)	0.86 (1.73)	Glass containers
S	38,700 (42,600)	38 (42)	0.99 (1.97)	Glass containers
Y	20,800 (22,900)	78 (86)	3.75 (7.51)	Glass containers
LL	171,000 (188,000)	247 (272)	1.45 (2.89)	Flat glass
MM	173,000 (190,000)	123 (135)	0.71 (1.42)	Flat glass
ZZ	23,300 (25,600)	233 (256)	10.0 (20.0)	Pressed and blown glass
ZZ	4,430 (4,870)	32 (35)	7.2 (14.4)	Pressed and blown glass
TOTALS	1,622,000 (1,784,170)	6,395 (7,034)	3.94 (7.88) (average)	
Total Glass Containers				
	1,108,000 (1,218,700)	4,269 (4,696)	3.85 (7.71) (average)	
Total Flat Glass				
	486,000 (535,000)	1,861 (2,047)	3.82 (7.65) (average)	
Total Pressed and Blown Glass				
	27,700 (30,470)	265 (291)	9.55 (19.10) (average)	

Table C-5. SOURCE TEST DATA FROM NEDS - SO_x EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production, metric tons/year (tons/year)	Emissions, metric tons/year (tons/year)	Emission factor, g/kg (lb/ton)	Product
A	46,200 (50,800)	27.3 (30)	0.59 (1.18)	Glass containers (two furnaces
A	15,900 (17,500)	8.2 (9)	0.52 (1.03)	Glass containers
C	31,900 (35,100)	16.4 (18)	0.52 (1.03)	Glass containers
C	11,800 (13,000)	6.4 (7)	0.54 (1.08)	Glass containers
C	34,800 (38,300)	17.3 (19)	0.49 (0.99)	Glass containers
C	47,900 (52,700)	24.6 (27)	0.52 (1.03)	Glass containers
D	143,000 (157,000)	450 (495)	3.15 (6.31)	Flat glass
F	40,100 (44,100)	94.6 (104)	2.36 (4.72)	Glass containers
F	47,700 (52,500)	12.3 (135)	2.57 (5.14)	Glass containers
L	41,100 (45,200)	10.9 (12)	0.27 (0.53)	Glass containers
L	30,100 (33,100)	9.1 (10)	0.30 (0.60)	Glass containers
K	27,500 (30,300)	10.9 (12)	0.40 (0.79)	Glass containers
K	34,800 (38,300)	10.9 (12)	0.32 (0.63)	Glass containers
K	71,200 (78,300)	52.7 (58)	0.74 (1.48)	Glass containers
N	81,800 (90,000)	177 (195)	2.17 (4.33)	Glass containers (three furnaces)
P	179,000 (197,000)	111 (122)	0.62 (1.24)	Glass containers (five furnaces)

Table C-5 (continued). SOURCE TEST DATA FROM NEDS - SO_x EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production, metric tons/year (tons/year)	Emissions, metric tons/year (tons/year)	Emission factor, g/kg (lb/ton)	Product
S	58,800 (64,700)	27.3 (30)	0.47 (0.93)	Glass containers
S	38,700 (42,600)	50.0 (55)	1.29 (2.58)	Glass containers
W	105,000 (115,000)	209 (230)	2.0 ( )	Glass containers
X	60,500 (66,500)	50 (55)	0.82 (1.65)	Glass containers
X	57,000 (63,000)	103 (113)	1.80 (3.59)	Glass containers
X	45,000 (49,000)	69.1 (76)	1.55 (3.10)	Glass containers
X	51,000 (56,000)	72.7 (80)	1.43 (2.86)	Glass containers
Y	40,300 (44,300)	8.2 (9)	0.21 (0.41)	Glass containers
Y	20,800 (22,900)	43.6 (48)	2.20 (4.19)	Glass containers
Z	34,600 (38,000)	145 (160)	4.21 (8.42)	Glass containers
Z	33,600 (37,000)	64.6 (71)	1.92 (3.84)	Glass containers
Z	52,000 (57,000)	96.4 (106)	1.86 (3.72)	Glass containers
Z	14,400 (15,800)	39.1 (43)	2.72 (5.44)	Glass containers
DD	126,000 (139,000)	37.3 (41)	0.30 (0.60)	Pressed and blown glassware (nine furnaces)
GG	37,000 (41,000)	38.2 (42)	1.03 (2.05)	Glass containers
JJ	73,400 (80,700)	53.6 (59)	0.73 (1.46)	Glass containers
JJ	99,000 (109,000)	45.5 (50)	0.46 (0.92)	Glass containers
JJ	35,400 (38,900)	10.2 (11)	0.29 (0.57)	Glass containers

Table C-5 (continued). SOURCE TEST DATA FROM NEDS - SO_x EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production, metric tons/year (tons/year)	Emissions, metric tons/year (tons/year)	Emission factor, g/kg (lb/ton)	Product
LL	171,000 (188,000)	756 (832)	4.43 (8.85)	Flat glass (three furnaces)
MM	173,000 (190,000)	539 (593)	3.12 (6.24)	Flat glass
TOTALS	2,106,021 (2,316,600)	3,399 (3,739)	1.62 (3.23)	(average)
Glass Containers				
	1,493,288 (1,642,600)	1,616 (1,778)	1.08 (2.16)	(average)
Flat Glass				
	486,400 (535,000)	1,745 (1,920)	3.59 (7.18)	(average)
Pressed and Blown Glass				
	126,400 (139,000)	37.3 (41)	0.30 (0.60)	(average)

deviation is ±1 g/kg (±2 lb/ton) and the 95% confidence limit is ±0.37 g/kg (0.75 lb/ton), the difference between the averages is not significant. An average value of 1.5 g/kg ± 0.4 g/kg (3 lb/ton) is used in the main text.

The averages at the end of Table C-5 for different types of glass indicate that flat glass has a higher SO_x emission factor (3.59 g/kg vs 1.08 for glass containers). This is because in the past flat glass has been made with twice the amount of salt cake (Na_2SO_4) as container glass, and the data in Table C-5 are primarily from 1972. However, manufacturers have reduced the amount of sulfate in the batch in order to lower emissions, and one producer now uses a salt cake content close to that for container glass.

In a recent sampling test on a typical float glass furnace, the SO_x emission factor was found to be 0.5 g/kg. Another producer (who apparently uses more salt cake) reported emission factors of 1.35 g/kg to 7.1 g/kg. It appears from these data, therefore, that an average emission factor of 1.5 g/kg is justified.

c. Particulates

Source test measurements of particulate emissions are given in Table C-6. Emission factors vary from 0.22 to 12.55 g/kg (0.44 to 25.1 lb/ton), with an average of 1.13 g/kg (2.27 lb/ton). However, a number of high values come from pressed and blown establishments which are known to make specialty glasses. (Plant V makes borosilicate glass and plants AA and EE make lead glass.) As a result, the average emission factor for soda-lime glass has been calculated by using data from flat glass plants and glass container

Table C-6. SOURCE TEST DATA FROM NEDS - PARTICULATE EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production metric tons/year (tons/year)	Emissions, metric tons/year (tons/year)	Emission factor, g/kg (lb/ton)	Product
A	46,200 (50,800)	35.5 (39)	0.77 (1.54)	Glass containers (two furnaces)
A	15,900 (17,500)	5.5 (6)	0.35 (0.69)	Glass containers
B	755,000 (830,000)	679 (747)	0.90 (1.80)	Glass containers (four furnaces)
C	31,900 (35,100)	23.6 (26)	0.74 (1.48)	Glass containers
C	11,800 (13,000)	9.1 (10)	0.77 (1.54)	Glass containers
C	34,800 (38,399)	26.4 (29)	0.75 (1.51)	Glass containers
C	47,900 (52,700)	36.4 (40)	0.76 (1.52)	Glass containers
D	143,000 (157,000)	105 (116)	0.74 (1.48)	Flat glass
F	40,100 (44,100)	23.6 (26)	0.59 (1.18)	Glass containers
F	47,700 (52,500)	26.4 (29)	0.55 (1.10)	Glass containers
N	82,000 (90,000)	303 (333)	3.70 (7.40)	Glass containers
J	68,100 (74,900)	43.6 (48)	0.64 (1.28)	Glass containers
J	65,500 (72,000)	48.2 (53)	0.73 (1.47)	Glass containers
K	27,500 (30,300)	19.1 (21)	0.70 (1.39)	Glass containers
K	34,800 (38,300)	33.6 (37)	0.97 (1.93)	Glass containers
K	71,200 (78,300)	61.8 (68)	0.87 (1.74)	Glass containers

Table C-6 (continued). SOURCE TEST DATA FROM NEDS - PARTICULATE EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production, metric tons/year (tons/year)	Emissions, metric tons/year (tons/year)	Emission factor, g/kg (lb/ton)	Product
L	41,100 (45,200)	35.5 (39)	0.87 (1.73)	Glass containers
L	30,100 (33,100)	22.7 (25)	0.76 (1.51)	Glass containers
M	66,200 (72,800)	36.4 (40)	0.55 (1.10)	Glass containers (two furnaces)
P	179,000 (197,000)	179 (197)	1.00 (2.00)	Glass containers (five furnaces)
R	78,400 (86,200)	38.2 (42)	0.49 (0.97)	Pressed and blown glassware
S	58,800 (64,700)	35.5 (39)	0.60 (1.21)	Glass containers
U	74,600 (82,000)	47.3 (52)	0.64 (1.27)	Glass containers
U	66,400 (73,000)	45.5 (50)	0.69 (1.37)	Glass containers
U	70,000 (77,000)	90 (99)	1.28 (2.57)	Glass containers
U	76,400 (84,000)	107 (118)	1.41 (2.81)	Glass containers
V	7,950 (8,750)	50 (55)	6.30 (12.60)	Pressed and blown technical glass
V	7,950 (8,750)	99 (110)	12.55 (25.10)	Pressed and blown technical glass
V	9,550 (10,500)	75 (82)	7.80 (15.60)	Pressed and blown technical glass

Table C-6 (continued). SOURCE TEST DATA FROM NEDS - PARTICULATE EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production, metric tons/year (tons/year)	Emissions, metric tons/year (tons/year)	Emission factor, g/kg (lb/ton)	Product
V	7,950 (8,750)	93 (102)	11.50 (23.00)	Pressed and blown technical glass
V	15,900 (17,500)	32 (35)	2.0 (4.00)	Pressed and blown technical glass
V	3,980 (4,380)	50 (55)	12.55 (25.10)	Pressed and blown technical glass
X	60,500 (66,500)	17 (19)	0.29 (0.57)	Glass containers
X	57,300 (63,000)	22 (24)	0.38 (0.76)	Glass containers
X	45,000 (49,000)	16 (18)	0.36 (0.73)	Glass containers
X	50,900 (56,000)	27 (30)	0.53 (1.07)	Glass containers
Y	40,300 (44,300)	27 (30)	0.68 (1.35)	Glass containers
Y	20,800 (22,900)	11 (12)	0.52 (1.05)	Glass containers
Z	73,000 (80,000)	57 (63)	0.79 (1.58)	Glass containers
Z	33,600 (37,000)	8 (9)	0.25 (0.49)	Glass containers
Z	51,800 (57,000)	25 (28)	0.49 (0.98)	Glass containers
Z	14,400 (15,800)	14 (15)	0.95 (1.90)	Glass containers
Z	34,600 (38,000)	26 (29)	0.76 (1.53)	Glass containers
AA	17,600 (19,400)	14 (16)	0.82 (1.64)	Pressed and blown glass

Table C-6 (continued). SOURCE TEST DATA FROM NEDS - PARTICULATE EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production, metric tons/year (tons/year)	Emissions, metric tons/year (tons/year)	Emission factor, g/kg (lb/ton)	Product
AA	4,630 (5,090)	21 (23)	4.52 (9.04)	Pressed and blown glass, lead glass
BB	29,900 (32,900)	63 (69)	2.10 (4.19)	Pressed and blown glass
CC	14,900 (16,400)	8 (9)	0.55 (1.10)	Pressed and blown glass
EE	29,100 (32,000)	44 (49)	1.53 (3.06)	Pressed and blown glass
EE	12,700 (14,000)	159 (175)	12.50 (25.00)	Pressed and blown glass
FF	109,000 (120,000)	120 (132)	1.1 (2.2)	Glass containers (four furnaces)
GG	39,300 (41,000)	35 (38)	0.93 (1.85)	Glass containers
HH	47,700 (52,500)	72 (79)	1.51 (3.01)	Pressed and blown glass
II	16,500 (18,100)	3.6 (4)	0.22 (0.44)	Glass containers
II	8,950 (9,850)	7 (8)	0.81 (1.62)	Glass containers
II	17,900 (19,700)	149 (164)	8.3 (16.6)	Glass containers
II	19,400 (21,300)	11 (12)	0.57 (1.13)	Glass containers
LL	171,000 (188,000)	154 (169)	0.90 (1.80)	Flat glass (three furnaces)

Table C-6 (continued). SOURCE TEST DATA FROM NEDS - PARTICULATE EMISSIONS FROM GLASS MELTING FURNACES[14]

Plant	Production, metric tons/year (tons/year)	Emissions, metric tons/year (tons/year)	Emission factor, g/kg (lb/ton)	Product
JJ	73,400 (80,700)	34 (37)	0.46 (0.92)	Glass containers
JJ	99,100 (109,000)	25 (28)	0.26 (0.51)	Glass containers
JJ	35,400 (38,900)	22 (24)	0.62 (1.23)	Glass containers
KK	64,900 (71,400)	112 (123)	1.73 (3.45)	Glass containers
KK	56,000 (61,600)	105 (115)	1.87 (3.73)	Glass containers
MM	173,000 (190,000)	398 (438)	2.31 (4.61)	Flat glass
TOTAL	3,932,400 (4,325,570)	4,470 (4,912)	1.14 (2.27)	(average)
Glass Containers				
	3,157,700 (3,473,450)	2,330 (2,563)	0.74 (1.48)	(average)
Flat Glass				
	486,400 (535,000)	1,315 (1,446)	1.35 (2.70)	(average)
Pressed and Blown Glass				
	288,300 (317,120)	821 (903)	2.85 (5.70)	(average)

plants. For these plants both weight and number average emission factors are 1.0 ± 0.6 g/kg (2.0 ± 1.2 lb/ton) at a 95% confidence limit. The standard deviation is ±2.3 g/kg (±4.5 lb/ton).

d. Carbon Monoxide

Source test data on CO emissions are scarce because this is not a major glass furnace emission. The high combustion temperature and the presence of excess air do not favor its formation.

Data are reported in ppm and cannot be converted directly to grams of CO per kilogram of glass because air flow rates are not given. A survey of NEDS showed that air flow rates varied from 1.4 to 8.2 standard m^3/kg (50,000 to 300,000 scf/ton) of glass. The wide range is due to such factors as furnace efficiency, electric boosting, percent excess air, and use of ejector air in the stack. An average value of 5.5 standard m^3 air/kg (200,000 scf air/ton) glass was used in the calculations because the furnaces tested were using ejector air.

Two test reports were not used in finding the average CO emission factor. One was a furnace melting borosilicate glass.[47] The other had CO concentrations of 40 ppm and 375 ppm in the stack gas,[33] and these values are 10 and 100 times higher than other data. A value of 375 ppm is equivalent to ~5 g/kg, which is inconsistent with good combustion conditions.

The emissions data are summarized in Table C-7. Because of the unknown air flow rates the accuracies are only estimates. (In addition, Reference 24 provided only a range of values for several tests.) A sample calculation follows:

Table C-7. CO EMISSIONS FROM GLASS MELTING FURNACES

Reference	CO emissions		Comments
	In stack gas, ppm	Glass produced, g/kg (lb/ton)	
24	0 - 5	0 - 0.04 (0 - 0.08)	Series of 16 tests on furnace melting 105 - 213 metric tons/day with and without carbon in the batch (@∿0.5 g/kg).
55	0 (11 runs) 5 (7 runs) 10 (1 run)	0 (0) 0.04 (0.08) 0.08 (0.16)	Tests on glass furnace melting ∿227 metric tons/day.
Average:	2.5 ppm	0.02 g/kg ± 100%	

Table C-8. HYDROCARBON EMISSIONS FROM GLASS MELTING FURNACES

Reference	Hydrocarbon emissions		Comments
	In stack gas, ppm	Glass produced, g/kg (lb/ton)	
24	0 - 5 (CH_4) 0 - 2 (As hexane)	0 - 0.02 (0 - 0.04) 0 - 0.05 (0 - 0.1)	Series of 16 tests on flint glass furnace melting 105 - 213 metric tons/day with and without carbon in the batch (@∿0.5 g/kg).
Average:		0.04 g/kg ± 100%	

[55] Bartz, D. R., K. W. Arledge, J. E. Gabrielson, L. G. Hays, and S. C. Hunter. Control of Oxides of Nitrogen from Stationary Sources in the South Coast Air Basin (of California). Prepared by KVB Engineering, Inc., for the Air Resources Board, Sacramento. Report No. ARB-R-2-1471-74-31 (PB 237688). September 1974. p. A-24.

> For 5 ppm CO and air flow of 200,000 scf/ton: this equals 1 scf CO/ton of glass. Since 1 scf = 28.32 liters and one gram mole of gas occupies 22.4 liters, this is equal to 1.264 gram moles of CO or 35.4 g or 0.08 lb.

The average emission factor for CO is 0.02 g/kg ± 100%. For comparison an emission factor was also computed from other data on gas-fired burners (see Table C-9). The CO emission factor is 9.45 ng/J (0.022 lb/million Btu ± 55%). Assuming a fuel consumption of 7 MJ/kg (6 million Btu/ton) of glass melted, this gives a factor of 0.066 g/kg ± 55%.

e. Hydrocarbons

There has been only one report of testing for hydrocarbons in the stack gas from the melting furnace (Table C-8). Since the data are in ppm the same assumptions were made as in the CO computations to find the emissions factor in g/kg. Examples are:

> For 5 ppm CH_4 and air flow of 6.24 standard m^3/kg (200,000 scf/ton): this equals 1 scf CH_4/ton of glass. Since 1 scf = 28.32 liter and one gram mole of gas occupies 22.4 liters, this is equal to 1.264 gram moles of CH_4 or 20.2 g (0.044 lb).
>
> For 2 ppm C_6H_{14} and air flow of 6.24 standard m^3/kg (200,000 scf/ton): this equals 0.4 scf hexane/ton of glass. Since 1 scf = 28.34 liters and one gram mole of gas occupies 22.4 liters, this is equal to 0.5056 gram moles of hexane or 43.5 g/or 0.096 lb.

The average emission factor for hydrocarbons is 0.04 g/kg ± 100%. For comparison an emission factor was also found using data from gas-fired burners (Table C-9). The average hydrocarbon emission factor from these is 6.0 ng/J (0.014 lb/million Btu ± 144%). Based on a fuel usage of 7 MJ/kg (6 million Btu/ton) of glass melted, the hydrocarbon emission factor will be 0.042 g/kg ± 144%.

3. FORMING AND FINISHING OPERATIONS - ANNEALING LEHRS

Since no emissions measurements have been made on gas-fired annealing lehrs, emission factors were estimated from other data on gas combustion. A modern recirculating air type lehr consumes 11 to 17 m^3/hr (400 cfh to 600 cfh) when annealing 91 metric tons (100 tons) of glass per day. Lehrs of the older design consume 34 to 57 m^3/hr (1,200 cfh to 2,000 cfh).[28] Using a worst case of 57 m^3/hr (2,000 cfh) gives a usage rate of 0.0062 m^3/kg (200 cubic ft/ton) of glass. For a typical flat glass plant making 500 metric tons (550 tons) of glass per day this amounts to 130 m^3/hr (4,583 cfh). With a heating value of 37.3 MJ/m^3 (1000 Btu/cubic ft) this can be converted to 1.34 MJ/sec (4,583,000 Btu/hr) or 0.23 MJ/kg (200,000 Btu/ton) of glass.

A series of tests on four gas-fired burners gave the emission data shown in Table C-9.[56] Converting these on a basis of 0.23 MJ/kg (200,000 Btu/ton) of glass annealed yields the emission factors in Table C-10.

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[56] Hangebrauck, R. P., D. J. Von Lehmden, and J. E. Meeker. Emissions of Polynuclear Hydrocarbons and other Pollutants from Heat-Generation and Incineration Processes. Journal of the Air Pollution Control Association 14:267-278, July 1964.

Table C-9. EMISSIONS FROM GAS-FIRED BURNERS [56]

Test	Emissions, ng/J (lb per million Btu)				
	NO_x	SO_x	Particulates[a]	CO	Hydrocarbons
15	60.2 (0.14)	-	9.0 (0.021)	5.6 (0.013)	1.29 (0.003)
17	150 (0.35)	0 (0)	2.58 (0.006)	8.6 (0.020)	-
18	38.7 (0.09)	0 (0)	3.0 (0.007)	11.2 (0.026)	9.5 (0.022)
19	25.8 (0.06)	-	11.2 (0.026)	12.9 (0.030)	6.9 (0.016)
Average and 95% confidence limits	69 (0.16) ±113%	0 (0)	5.2 (0.012) ±196%	9.5 (0.022) ±55%	6.0 (0.014) ±144%
Standard deviation	±47 (±0.11)	0 (0)	±5.2 (±0.012)	±2.75 (±0.0064)	±3.4 (±0.0079)

[a] It is thought that the particulates are present in the inlet air and not formed during the combustion process.

Table C-10. EMISSION FACTORS FOR ANNEALING LEHRS

Emission	Emission factor,	
	mg/kg	(lb/ton)
NO_x	16 ± 113%	(0.032)
SO_x	0	(0)
Particulates	1.2 ± 196%	(0.0024)
CO	2.2 ± 55%	(0.0044)
Hydrocarbons	1.4 ± 144%	(0.0028)

APPENDIX D

TOTAL FLAT GLASS EMISSIONS

Total flat glass emissions were compared on a state and national basis to emissions from all stationary sources. State emissions were calculated by assuming that state production was proportional to the state capacities listed in Appendix B. The state production percentage was then multiplied by the national emissions in Table 11 to give state emissions for NO_x, SO_x, and particulates. Values for CO and hydrocarbons were not calculated because they were all <0.01.

Table D-1 gives the breakdown of NO_x, SO_x, and particulates by state. Total state emissions were taken from the NEDS inventory,[57] which is shown in Table D-2. Emission ratios appear in Table D-1. Another comparison was made using an emissions data base generated by Monsanto Research Corporation,[58] and this is given in Table D-3.

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[57] 1972 National Emissions Report. Environmental Protection Agency. Research Triangle Park. Publication No. EPA-450/2-74-012. June 1974. 422 p.

[58] State-by-State Listing of Source Types that Exceed the Third Decision Criteria. Special Project Report Prepared by Monsanto Research Corporation for the Environmental Protection Agency, Research Triangle Park. Contract 68-02-1874. July 1975. p. 1-3.

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Table D-1. STATE BY STATE LISTING OF EMISSIONS

		Annual production		Emissions, metric tons			NEDS % of state emissions			MRC % of state emissions		
State	Capacity, metric tons/day	%	10^3 metric tons	NO_x	SO_x	Particulates	NO_x	SO_x	Particulates	NO_x	SO_x	Particulates
Arkansas	200	1.4	57	224	84	56	0.1	0.2	<0.1	0.3	<0.1	<0.1
California	824	5.8	232	928	348	232	<0.1	0.1	<0.1	0.1	<0.1	<0.1
Illinois	720	5.0	201	800	300	200	0.1	<0.1	<0.1	0.1	<0.1	<0.1
Maryland	360	2.5	101	400	150	100	0.5	<0.1	<0.1	0.2	<0.1	<0.1
Michigan	1,180	8.2	328	1,312	492	328	<0.1	<0.1	<0.1	0.2	<0.1	<0.1
Missouri	807	5.6	226	896	336	224	0.2	<0.1	0.1	0.3	<0.1	<0.1
New Jersey	450	3.2	126	512	192	128	0.1	<0.1	0.1	0.2	<0.1	<0.1
North Carolina	680	4.7	189	752	282	188	0.2	0.1	<0.1	0.2	<0.1	<0.1
Ohio	1,900	13.3	533	2,128	798	532	0.2	<0.1	<0.1	0.3	<0.1	<0.1
Oklahoma	1,060	7.4	298	1,184	444	296	0.5	0.3	0.3	0.9	0.3	<0.1
Pennsylvania	2,235	15.6	624	2,496	936	624	0.1	<0.1	<0.1	0.3	<0.1	<0.1
Tennessee	2,439	17.0	680	2,720	1,020	680	0.6	0.1	0.2	1.0	0.1	<0.1
Texas	900	6.3	252	1,008	378	252	0.1	<0.1	<0.1	0.1	<0.1	<0.1
West Virginia	540	3.8	151	608	228	152	0.5	<0.1	0.1	0.2	<0.1	<0.1
United States	14,290	100	4,000	16,000	6,000	4,000	0.07	0.02	0.02	0.14	0.009	0.003

Table D-2. NEDS EMISSION SUMMARY BY STATE[57]
(metric tons)

	Particulates	SO_x	NO_x	HC	CO
Alabama	1,178,643	882,731	397,068	643,410	1,885,657
Alaska	13,913	5,874	32,757	28,389	167,357
Arizona	72,685	1,679,768	123,871	189,981	815,454
Arkansas	137,817	39,923	168,989	195,538	843,204
California	1,006,452	393,326	1,663,139	2,160,710	8,237,667
Colorado	201,166	49,188	147,496	193,456	875,781
Connecticut	40,074	168,068	155,832	219,661	897,580
Delaware	36,808	209,310	58,407	63,886	204,227
Dist. Columbia	19,451	60,630	46,824	41,789	190,834
Florida	226,460	897,381	644,794	619,872	2,695,817
Georgia	404,574	472,418	369,817	458,010	2,036,010
Hawaii	61,621	45,981	44,221	89,530	275,566
Idaho	55,499	54,387	48,552	84,230	343,720
Illinois	1,143,027	2,043,020	974,372	1,825,913	6,412,718
Indiana	748,405	2,050,541	1,371,233	600,477	2,933,780
Iowa	216,493	283,416	242,524	316,617	1,440,621
Kansas	348,351	86,974	233,987	309,633	1,002,375
Kentucky	546,214	1,202,827	419,142	326,265	1,189,932
Louisiana	380,551	166,664	442,817	1,919,662	5,633,827
Maine	49,155	144,887	76,741	122,918	376,196
Maryland	494,921	420,037	265,204	295,867	1,261,804
Massachusetts	96,160	636,466	334,379	440,481	1,682,218
Michigan	705,921	1,466,935	2,222,438	717,891	3,243,526
Minnesota	266,230	391,633	311,834	410,674	1,760,749
Mississippi	168,355	50,591	172,519	195,950	829,094
Missouri	202,435	1,152,373	448,300	413,130	1,854,901
Montana	272,688	871,235	148,405	271,824	611,061
Nebraska	95,338	58,014	101,948	127,821	569,522
Nevada	94,040	304,851	88,933	53,673	215,751
New Hampshire	14,920	86,596	67,309	88,469	256,380

Table D-2 (Continued). NEDS EMISSION SUMMARY BY STATE[57]

(metric tons)

	Particulates	SO_x	NO_x	HC	CO
New Jersey	151,768	463,736	489,216	819,482	2,877,319
New Mexico	102,785	444,310	199,181	152,057	504,249
New York	160,044	345,979	572,451	1,262,206	4,881,922
North Carolina	481,017	473,020	412,599	447,238	1,734,398
North Dakota	78,978	78,537	85,708	70,289	318,679
Ohio	1,766,056	2,980,333	1,101,470	1,153,493	5,205,719
Oklahoma	93,595	130,705	222,687	341,358	1,456,627
Oregon	169,449	36,776	135,748	234,669	929,247
Pennsylvania	1,810,598	2,929,137	3,017,345	891,763	3,729,830
Rhode Island	13,073	65,761	46,921	65,833	283,650
South Carolina	198,767	247,833	521,544	907,833	4,222,168
South Dakota	52,336	17,354	49,490	90,478	387,356
Tennessee	409,704	1,179,982	426,454	362,928	1,469,253
Texas	549,399	753,098	1,303,801	2,218,891	6,897,748
Utah	71,692	152,526	80,998	98,282	402,527
Vermont	14,587	17,751	24,286	41,980	150,510
Virginia	477,494	447,394	329,308	369,416	1,548,031
Washington	161,934	272,991	187,923	344,643	1,659,117
West Virginia	213,715	678,348	229,598	116,155	494,214
Wisconsin	411,558	712,393	408,525	523,930	1,582,869
Wyoming	75,427	69,394	72,572	55,319	303,297
U.S. TOTALS	16,762,000	28,873,000	21,722,000	23,994,000	91,782,000

ADJUSTMENTS TO GRAND TOTAL

The United States summary does not include certain source categories. The following additions should be considered part of the United States grand total for a more accurate picture of nationwide emissions.

	Particulates	SO_x	NO_x	HC	CO
New York pt. sources	311,000	993,000	382,000	127,000	44,000
Forest wild fires	375,000	0	88,000	529,000	3,089,000
Agricultural burning	272,000	15,000	29,000	272,000	1,451,000
Structural fires	52,000	0	6,000	61,000	200,000
Coal refuse fires	100,000	128,000	31,000	62,000	308,000
Total	1,110,000	1,076,000	536,000	1,051,000	5,086,000
U.S. Subtotal (above)	16,762,000	28,873,000	21,722,000	23,994,000	91,782,000
U.S. Grand Total	17,872,000	29,949,000	22,258,000	25,045,000	96,868,000

Table D-3. STATE LISTING OF EMISSIONS AS OF JULY 2, 1975[58]

State	Mass of emissions, metric tons/yr (upper entry) Percent of U.S. totals (lower entry)				
	Particulate	SO_2	NO_x	Hydrocarbons	CO
1 ALABAMA	2002000.0 1.53000	1228000.0 1.91000	261600.0 2.27000	342100.0 1.29000	372600.0 2.04000
2 ALASKA	16340000.0 12.50000	222800.0 0.34700	31990.0 0.27700	140800.0 0.53200	472200.0 2.58000
3 ARIZONA	3265000.0 2.49000	200200.0 0.31100	75100.0 0.65100	171100.0 0.64700	178300.0 0.97600
4 ARKANSAS	1619000.0 1.24000	205400.0 0.31900	77310.0 0.67000	281700.0 1.07000	225800.0 1.24000
5 CALIFORNIA	5675000.0 4.33000	2557000.0 3.98000	796800.0 6.91000	1914000.0 7.24000	1987000.0 10.90000
6 COLORADO	3156000.0 2.41000	473300.0 0.73600	116800.0 1.01000	294400.0 1.11000	105800.0 0.57900
7 CONNECTICUT	365600.0 0.27900	1227000.0 1.91000	152200.0 1.32000	259400.0 0.98100	92690.0 0.50700
8 DELAWARE	130200.0 0.09930	420700.0 0.65500	45720.0 0.39600	77510.0 0.29300	24580.0 0.13500
9 FLORIDA	2430000.0 1.86000	1755000.0 2.73000	410300.0 3.56000	536200.0 2.03000	3502000.0 19.20000
10 GEORGIA	2331000.0 1.78000	1635000.0 2.54000	294200.0 2.55000	526700.0 1.99000	705400.0 3.86000
11 HAWAII	251200.0 0.19200	232000.0 0.36100	40790.0 0.35400	62720.0 0.23700	84750.0 0.46400
12 IDAHO	2430000.0 1.85000	59140.0 0.09200	33220.0 0.28800	163600.0 0.61900	518300.0 2.84000
13 ILLINOIS	3584000.0 2.74000	3714000.0 5.78000	665100.0 5.77000	1343000.0 5.08000	412500.0 2.26000
14 INDIANA	2202000.0 1.68000	3036000.0 4.72000	414400.0 3.59000	675100.0 2.55000	182100.0 0.99700
15 IOWA	2579000.0 1.97000	397400.0 0.61800	137700.0 1.19000	400800.0 1.52000	90720.0 0.49700
16 KANSAS	3358000.0 2.56000	225000.0 0.35000	109900.0 0.95300	742800.0 2.81000	174600.0 0.95600
17 KENTUCKY	1854000.0 1.42000	1627000.0 2.53000	302000.0 2.62000	274600.0 1.04000	219300.0 1.20000

Table D-3 (continued). STATE LISTING OF EMISSIONS AS OF JULY 2, 1975[58]

State	Mass of emissions, metric tons/yr (upper entry) Percent of U.S. totals (lower entry)				
	Particulate	SO_2	NO_x	Hydrocarbons	CO
18 LOUISIANA	1651000.0 1.26000	585800.0 0.91100	219000.0 1.90000	1741000.0 6.58000	839900.0 4.60000
19 MAINE	1038000.0 0.79200	770700.0 1.20000	54270.0 0.47000	71970.0 0.27200	61430.0 0.33600
20 MARYLAND	657300.0 0.50200	1352000.0 2.10000	215100.0 1.86000	302300.0 1.14000	163400.0 0.89400
21 MASSACHUSETTS	802700.0 0.61300	3840000.0 5.97000	322300.0 2.79000	463100.0 1.75000	190400.0 1.04000
22 MICHIGAN	2804000.0 2.14000	3513"00.0 5.46000	548000.0 4.75000	734000.0 2.78000	299400.0 1.64000
23 MINNESOTA	3056000.0 2.33000	846800.0 1.32000	185000.0 1.60000	388000.0 1.47000	150700.0 0.82500
24 MISSISSIPPI	1490000.0 1.14000	280300.0 0.43600	87010.0 0.75400	350200.0 1.32000	228200.0 1.25000
25 MISSOURI	2839000.0 2.17000	1259000.0 1.96000	287500.0 2.49000	588400.0 2.22000	268500.0 1.47000
26 MONTANA	4975000.0 3.80000	177000.0 0.27500	34650.0 0.30000	174200.0 0.65800	230500.0 1.26000
27 NEBRASKA	3049000.0 2.33000	137100.0 0.21300	50940.0 0.44200	255600.0 0.96600	59590.0 0.32600
28 NEVADA	3155000.0 2.41000	263100.0 0.40900	58500.0 0.50700	36140.0 0.13700	28700.0 0.15700
29 NEW HAMPSHIRE	326500.0 0.24900	325800.0 0.50700	36060.0 0.31300	44430.0 0.16800	30200.0 0.16500
30 NEW JERSEY	815800.0 0.62300	2922000.0 4.55000	323400.0 2.80000	786600.0 2.97000	281400.0 1.54000
31 NEW MEXICO	3548000.0 2.71000	441400.0 0.68700	109800.0 0.95200	310200.0 1.17000	49460.0 0.27100
32 NEW YORK	2704000.0 2.06000	5137000.0 7.99000	721400.0 6.25000	1353000.0 5.11000	551600.0 3.02000
33 N CAROLINA	2203000.0 1.68000	2298000.0 3.58000	338400.0 2.93000	465100.0 1.76000	371500.0 2.03000
34 N DAKOTA	2854000.0 2.18000	328700.0 0.51100	61110.0 0.53000	73930.0 0.28000	22320.0 0.12200
35 OHIO	3054000.0 2.33000	4062000.0 6.32000	785800.0 6.81000	1244000.0 4.70000	482700.0 2.64000
36 OKLAHOMA	2276000.0 1.74000	163400.0 0.25400	130000.0 1.13000	674700.0 2.55000	200800.0 1.10000
37 OREGON	2885000.0 2.20000	372500.0 0.57900	62710.0 0.54400	204800.0 0.77400	304900.0 1.67000

Table D-3 (continued). STATE LISTING OF EMISSIONS AS OF JULY 2, 1975[58]

State	Mass of emissions, metric tons/yr (upper entry) Percent of U.S. totals (lower entry) Particulate	 SO_2	 NO_x	 Hydrocarbons	 CO
38 PENNSYLVANIA	3132000.0 2.39000	5603000.0 8.72000	782200.0 6.78000	1331000.0 5.03000	527000.0 2.88000
39 RHODE ISLAND	113200.0 0.08640	519900.0 0.80900	38760.0 0.33600	93730.0 0.35400	29390.0 0.16100
40 S CAROLINA	1209000.0 0.92300	1076000.0 1.67000	146300.0 1.27000	260500.0 0.98500	483900.0 2.65000
41 S DAKOTA	2861000.0 2.18000	69420.0 0.10800	18560.0 0.16100	91110.0 0.34400	23480.0 0.12900
42 TENNESSEE	1789000.0 1.37000	1307000.0 2.03000	264100.0 2.29000	340900.0 1.29000	200300.0 1.10000
43 TEXAS	9302000.0 7.10000	1817000.0 2.83000	695500.0 6.05000	4139000.0 15.60000	1501000.0 8.22000
44 UTAH	2461000.0 1.88000	285400.0 0.44400	48410.0 0.42000	112800.0 0.42600	46840.0 0.25600
45 VERMONT	292100.0 0.22300	112600.0 0.17500	13710.0 0.11900	25460.0 0.09630	14190.0 0.07770
46 VIRGINIA	1607000.0 1.23000	1388000.0 2.16000	197800.0 1.71000	415200.0 1.57000	235100.0 1.29000
47 WASHINGTON	2204000.0 1.68000	626400.0 0.97500	126300.0 1.09000	361800.0 1.37000	425500.0 2.33000
48 W VIRGINIA	1261000.0 0.96200	1455000.0 2.26000	306500.0 2.66000	172800.0 0.65300	435100.0 2.38000
49 WISCONSIN	2180000.0 1.66000	1216000.0 1.89000	231300.0 2.00000	362600.0 1.37000	161300.0 0.88300
50 WYOMING	2851000.0 2.18000	513000.0 0.79800	70570.0 0.61200	275200.0 1.04000	20870.0 0.11400
US TOTALS	131000000.0	64300000.0	11500000.0	26400000.0	18300000.0

APPENDIX E

PLUME RISE CORRECTION

The Gaussian plume equation that is used to predict ground level concentrations contains a factor called the effective stack height, H. This is equal to the physical stack height (h) plus the amount of plume rise (ΔH).

$$H = h + \Delta H$$

An exhaust plume rises before dispersal due to its exit velocity and temperature. In the case of glass furnaces this is a significant effect ($\Delta H/h > 50\%$).

Plume rise can be estimated from the Holland formula[40]

$$\Delta H = \frac{V_s D_i}{u} \left(1.5 + 2.68 \times 10^{-3} p \, \frac{T_s - T_a}{T_s} D_i\right)$$

where V_s = stack gas exit velocity, m/sec

D_i = inside stack diameter, m

u = wind speed, m/sec

p = atmospheric pressure, mb

T_s = stack gas temperature, °K

T_a = ambient temperature, °K

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Under C class stability conditions ΔH is increased by a correction factor of 1.10.

Table E-1 presents stack gas parameters for 12 flat glass furnaces and the corresponding plume rise. The variation in stack gas temperature and exit velocity is partly caused by the use of ejection air. In the calculations the ambient temperature was taken to be 294°K (70°F), the wind speed 4.5 m/sec, and the pressure 1,013 mb (1 atmosphere).

Table E-1. PLUME RISE FOR FLAT GLASS FURNACES[14,a]

Stack	Height, m	Diameter, m	V_s, m/sec	T_s, °K	ΔH, m
1	83.8	2.44	16.64	942	60.1
2	51.8	2.74	2.40	589	8.4
3	64.9	2.44	12.17	858	42.5
4	64.3	2.44	9.99	778	33.5
5	64.3	2.44	10.62	797	36.0
6	76.2	2.44	9.10	753	30.0
7	34.4	2.74	14.33	450	39.1
8	67.1	2.13	4.04	781	10.7
9	61.3	2.29	10.89	783	32.8
10	61.0	2.59	8.06	756	29.6
11	28.8	2.54	14.3	438	33.5
12	27.4	1.78	15.0	598	25.7
Average					30

[a] Additional data supplied by a flat glass manufacturer.

APPENDIX F

DERIVATION OF SOURCE SEVERITY EQUATIONS

(T. R. Blackwood and E. C. Eimutis)

1. SUMMARY OF SEVERITY EQUATIONS

The maximum severity of pollutants may be calculated using the mass emission rate, Q, the height of the emissions, H, and the ambient air quality standard (AAQS). The equations summarized in Table F-1 are developed in detail in this appendix.

Table F-1. POLLUTANT SEVERITY EQUATIONS

Pollutant	Severity equation
For elevated sources:	
Particulate	$\frac{70\ Q}{H^2}$
SO_x	$\frac{50\ Q}{H^2}$
NO_x	$\frac{315\ Q}{H^{2.1}}$
HC	$\frac{162\ Q}{H^2}$
CO	$\frac{0.78\ Q}{H^2}$

2. DERIVATION OF χ_{max} FOR USE WITH U.S. AVERAGE CONDITIONS

The most widely accepted formula for predicting downwind ground level concentrations from a point source is:[40]

$$\chi = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad \text{(F-1)}$$

where χ = downwind ground level concentration at reference coordinate x and y with emission height of H, g/m^3

Q = mass emission rate, g/s

σ_y = standard deviation of horizontal dispersion, m

σ_z = standard deviation of vertical dispersion, m

u = wind speed, m/s

y = horizontal distance from centerline of dispersion, m

H = height of emission release (effective stack height), m

x = downwind dispersion distance from source of emission release, m

π = 3.14

We assume that χ_{max} occurs when $x >> 0$ and $y = 0$. For a given stability class, standard deviations of horizontal and vertical dispersion have often been expressed as a function of downwind distance by power law relationships as follows:[59]

$$\sigma_y = ax^b \qquad \text{(F-2)}$$

$$\sigma_z = cx^d + f \qquad \text{(F-3)}$$

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[59] Martin, D. O., and J. A. Tikvart, A. General Atmospheric Diffusion Model for Estimating the Effects of Air Quality of One or More Sources. (Presented at 61st Annual Meeting of the Air Pollution Control Association, for NAPCA, St. Paul, 1968.) 18 p.

Values for a, b, c, d and f are given in Tables F-2 and F-3. Substituting these general equations into Eq. F-1 yields:

$$\chi = \frac{Q}{ac\pi ux^{b+d} + a\pi ufx^{b}} \exp -\left[\frac{H^2}{2(cx^{d} + f)^2}\right] \qquad \text{(F-4)}$$

Assuming that χ_{max} occurs at $x<100$m or the stability class is C, then $f = 0$ and Equation F-4 becomes:

$$\chi = \frac{Q}{ac\pi ux^{b+d}} \exp \frac{-H^2}{2c^2x^{2d}} \qquad \text{(F-5)}$$

For convenience, let:

$$A_R = \frac{Q}{ac\pi u} \text{ and } B_R = \left[\frac{-H^2}{2c^2}\right]$$

so that Equation F-5 reduces to:

$$\chi = A_R x^{-(b+d)} \exp\left[\frac{B_R}{x^{2d}}\right] \qquad \text{(F-6)}$$

Table F-2. VALUES OF a FOR THE COMPUTATION OF σ_y[a,60]

Stability class	a
A	0.3658
B	0.2751
C	0.2089
D	0.1471
E	0.1046
F	0.0722

[a] For the equation

$$\sigma_y = ax^b$$

where x = downwind distance

$b = 0.9031$

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[60] Tadmor, J. and Y. Gur. Analytical Expressions for the Vertical and Lateral Dispersion Coefficients in Atmospheric Diffusion. Atmospheric Environment, 3:688-689, 1969.

Table F-3. VALUES OF THE CONSTANTS USED TO ESTIMATE VERTICAL DISPERSIONS[a,59]

Usable range	Stability class	Coefficient		
		c_1	d_1	f_1
>1,000 m	A	0.00024	2.094	-9.6
	B	0.055	1.098	2.0
	C	0.113	0.911	0.0
	D	1.26	0.516	-13
	E	6.73	0.305	-34
	F	18.05	0.18	-48.6
		c_2	d_2	f_2
100-1,000 m	A	0.0015	1.941	9.27
	B	0.028	1.149	3.3
	C	0.113	0.911	0.0
	D	0.222	0.725	-1.7
	E	0.211	0.678	-1.3
	F	0.086	0.74	-0.35
		c_3	d_3	
<100 m	A	0.192	0.936	
	B	0.156	0.922	
	C	0.116	0.905	
	D	0.079	0.881	
	E	0.063	0.871	
	F	0.053	0.814	

[a] For the equation:

$$\sigma_z = cx^d + f$$

Taking the first derivative of Equation F-6

$$\frac{d\chi}{dx} = A_R \left\{ x^{-b-d} \left(\exp \left[B_R x^{-2d}\right]\right) \left(-2dB_R x^{-2d-1}\right) + \exp \left[B_R x^{-2d}\right] \left(-b-d\right) x^{-b-d-1} \right\} \qquad \text{(F-7)}$$

and setting this equal to zero (to determine the roots which give the minimum and maximum conditions of χ with respect to x) yields:

$$\frac{d\chi}{dx} = 0 = A_R x^{-b-d-1} \left(\exp\left[B_R x^{-2d}\right]\right) \left[-2dB_R x^{-2d} - b - d\right] \qquad \text{(F-8)}$$

Since we define that $x \neq 0$ or ∞ at χ_{max}, the following expression must be equal to 0:

$$-2dB_R x^{-2d} - d - b = 0 \qquad \text{(F-9)}$$

or

$$\left(b+d\right) x^{2d} = -2dB_R \qquad \text{(F-10)}$$

or

$$x^{2d} = \frac{-2dB_R}{b+d} = \frac{2d\ H^2}{2c^2(b+d)} \qquad \text{(F-11)}$$

or

$$x^{2d} = \frac{d\ H^2}{c^2(b+d)} \qquad \text{(F-12)}$$

or

$$x = \left(\frac{d\ H^2}{c^2(b+d)}\right)^{\frac{1}{2d}} \text{ at } \chi_{max} \qquad \text{(F-13)}$$

Thus Equations F-2 and F-3 become:

$$\sigma_y = a\left(\frac{d\ H^2}{c^2(d+b)}\right)^{\frac{b}{2d}} \qquad \text{(F-14)}$$

$$\sigma_z = c\left(\frac{d\ H^2}{c^2(b+d)}\right)^{\frac{d}{2d}} = \left(\frac{d\ H^2}{b+d}\right)^{\frac{1}{2}} \qquad \text{(F-15)}$$

The maximum will be determined for U.S. average conditions of stability. According to Slade[61], this is when $\sigma_y = \sigma_z$.

Since b = 0.9031, and upon inspection of Table F-2 under U.S. average conditions, $\sigma_y = \sigma_z$, it can be seen that $0.881 \leq d \leq 0.905$ (class C stability[a]). Thus, it can be assumed that b is nearly equal to d or:

$$\sigma_z = \frac{H}{\sqrt{2}} \qquad \text{(F-16)}$$

and

$$\sigma_y = \frac{a}{c}\frac{H}{\sqrt{2}}$$

Under U.S. average conditions, $\sigma_y = \sigma_z$ and $a \simeq c$ if $b \simeq d$ and f = 0 (between class C and D, but closer to belonging in class C).

Then

$$\sigma_y = \frac{H}{\sqrt{2}}$$

Substituting for σ_y and σ_z into Equation F-1 and letting y = 0:

$$\chi_{max} = \frac{2\ Q}{\pi u H^2} \exp\left[-\frac{1}{2}\left(\frac{H\sqrt{2}}{H}\right)^2\right] \qquad \text{(F-19)}$$

or

$$\chi_{max} = \frac{2\ Q}{\pi e u H^2} \qquad \text{(F-20)}$$

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[a] The values given in Table F-3 are mean values for stability class. Class C stability describes these coefficients and exponents, only within about a factor of two[15].)

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[61] Gifford, F. A., Jr. An Outline of Theories of Diffusion in the Lower Layers of the Atmosphere. In: Meteorology and Atomic Energy 1968, Chapter 3, Slade, D. A. (ed.). Oak Ridge, Tennessee, U.S. Atomic Energy Commission Technical Information Center. Publication No. TID-24190. July 1968. p. 113.

3. DEVELOPMENT OF SOURCE SEVERITY EQUATIONS

The general source severity, S, relationship has been defined as follows:

$$S = \frac{\bar{\chi}_{max}}{AAQS} \qquad \text{(F-21)}$$

where $\bar{\chi}_{max}$ = average maximum ground level concentration

AAQS = ambient air quality standard

As mentioned in the main text, values of $\bar{\chi}_{max}$ are found from the equation

$$\bar{\chi}_{max} = \chi_{max} \left(\frac{t_0}{t}\right)^{0.17} \qquad \text{(F-22)}$$

where t_0 is the "instantaneous" (i.e. 3 minute) averaging time and t is the averaging time used for the ambient air quality standard. These are given in Table F-4.

(1) CO Severity - The primary standard for CO is reported for a 1-hr averaging time. Therefore,

$$t = 60 \text{ min}$$

$$\bar{\chi}_{max} = \chi_{max} \left(\frac{3}{60}\right)^{0.17} \qquad \text{(F-23)}$$

$$= \frac{2\,Q}{\pi e u H^2} \left(\frac{3}{60}\right)^{0.17} \qquad \text{(F-24)}$$

$$= \frac{2\,Q}{(3.14)(2.72)(4.5)\,H^2} \;(0.6) \qquad \text{(F-25)}$$

Table F-4. SUMMARY OF NATIONAL AMBIENT AIR QUALITY STANDARDS[62]

Pollutant	Averaging time	Primary standards	Secondary standards
Particulate matter	Annual (Geometric mean)	75 $\mu g/m^3$	60[a] $\mu g/m^3$
	24-hour[b]	260 $\mu g/m^3$	150 $\mu g/m^3$
Sulfur oxides	Annual (arithmetic mean)	80 $\mu g/m^3$ (0.03 ppm)	60 $\mu g/m^3$ (0.02 ppm)
	24-hour[b]	365 $\mu g/m^3$ (0.14 ppm)	260[c] $\mu g/m^3$ (0.1 ppm)
	3-hour[b]	-	1300 $\mu g/m^3$ (0.5 ppm)
Carbon monoxide	8-hour[b]	10 mg/m^3 (9 ppm)	
	1-hour[b]	40 mg/m^3 (35 ppm)	(Same as primary)
Nitrogen dioxide	Annual (arithmetic mean)	100 $\mu g/m^3$ (0.05 ppm)	(Same as primary)
Photochemical oxidants	1-hour[b]	160 $\mu g/m^3$ (0.08 ppm)	(Same as primary)
Hydrocarbons (nonmethane)	3-hour (6 to 9 a.m.)	160 $\mu g/m^3$ (0.24 ppm)	(Same as primary)

[a] The secondary annual standard (60 $\mu g/m^3$) is a guide for assessing implementation plans to achieve the 24-hour secondary standard.

[b] Not to be exceeded more than once per year.

[c] The secondary annual standard (260 $\mu g/m^3$) is a guide for assessing implementation plans to achieve the annual standard.

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[62] Code of Federal Regulations, Title 42 - Public Health, Chapter IV - Environmental Protection Agency, Part 410 National Primary and Secondary Ambient Air Quality Standards, April 28, 1971. 16 p.

$$= \frac{0.052\ Q}{H^2}\ (0.6) \qquad \text{(F-26)}$$

$$\bar{X}_{max} = \frac{(3.12 \times 10^{-2})Q}{H^2} \qquad \text{(F-27)}$$

Substituting the primary standard for CO (0.04 g/m^3) into the equation for S then gives:

$$S = \frac{\bar{X}_{max}}{AAQS} = \frac{(3.12 \times 10^{2})Q}{0.04\ H^2} \qquad \text{(F-28)}$$

or

$$S_{CO} = \frac{0.78\ Q}{H^2} \qquad \text{(F-29)}$$

(2) Hydrocarbon Severity - The primary standard for hydrocarbon is reported for a 3-hr averaging time.

$$t = 180 \text{ min}$$

$$\bar{X}_{max} = X_{max} \left(\frac{3}{180}\right)^{0.17} \qquad \text{(F-30)}$$

$$= 0.5 X_{max} \qquad \text{(F-31)}$$

$$= \frac{(0.5)(0.052)\ Q}{H^2} \qquad \text{(F-32)}$$

$$\bar{X}_{max} = \frac{0.026\ Q}{H^2} \qquad \text{(F-33)}$$

For hydrocarbons, AAQS = 1.6×10^{-4} g/m^3

and

$$S = \frac{\overline{\chi}_{max}}{AAQS} = \frac{0.026\ Q}{1.6 \times 10^{-4} H^2} \qquad (F\text{-}34)$$

or

$$S_{HC} = \frac{162.5\ Q}{H^2} \qquad (F\text{-}35)$$

(3) Particulate Severity - The primary standard for particulate is reported for a 24-hr averaging time.

$$\overline{\chi}_{max} = \chi_{max} \left(\frac{3}{1440}\right)^{0.17} \qquad (F\text{-}36)$$

$$= \frac{(0.052)\ Q}{H^2} (0.35) \qquad (F\text{-}37)$$

$$\overline{\chi}_{max} = \frac{(0.0182)\ Q}{H^2} \qquad (F\text{-}38)$$

For particulates, AAQS = 2.6×10^{-4} g/m^3

$$S = \frac{\overline{\chi}_{max}}{AAQS} = \frac{0.0182\ Q}{2.6 \times 10^{-4}\ H^2} \qquad (F\text{-}39)$$

$$S_P = \frac{70\ Q}{H^2} \qquad (F\text{-}40)$$

(4) SO_x Severity - The primary standard for SO_x is reported for a 24-hr averaging time.

$$\bar{\chi}_{max} = \frac{(0.0182)\ Q}{H^2} \qquad \text{(F-41)}$$

The primary standard is 3.65×10^{-4} g/m^3.

and

$$S = \frac{\bar{\chi}_{max}}{AAQS} = \frac{(0.0182)\ Q}{3.65 \times 10^{-4}\ H^2} \qquad \text{(F-42)}$$

or

$$S_{SO_x} = \frac{50\ Q}{H^2} \qquad \text{(F-43)}$$

(5) NO_x Severity - Since NO_x has a primary standard with a 1-yr averaging time, the χ_{max} correction equation cannot be used. As an alternative, the following equation was selected:

$$\bar{\chi} = \frac{2.03\ Q}{\sigma_z u x} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)\right]^2 \qquad \text{(F-44)}$$

A difficulty arises, however, because a distance x, from emission point to receptor, is included and hence, the following rationale is used:

The equation $\chi_{max} = \frac{2\ Q}{\pi e u H^2}$

is valid for neutral conditions or when $\sigma_z \approx \sigma_y$. This maximum occurs when

$$H \approx \sqrt{2}\sigma_z$$

and since, under these conditions,

$$\sigma_z = ax^b$$

then the distance x_{max} where the maximum concentration occurs is:

$$x_{max} = \left(\frac{H}{\sqrt{2a}}\right)^{\frac{1}{b}}$$

For class C conditions,

$$a = 0.113$$

$$b = 0.911$$

Simplifying Equation F-44

since $\qquad \sigma_z = 0.113\ x_{max}{}^{0.911}$

and $\qquad u = 4.5$ m/sec

Letting $x = x_{max}$ in Equation F-44,

$$\chi_{max} = \frac{4\ Q}{x_{max}{}^{1.911}} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad \text{(F-45)}$$

$$x_{max} = \frac{H^{1.098}}{0.16} \qquad \text{(F-46)}$$

$$x_{max} = 7.5\ H^{1.098} \qquad \text{(F-47)}$$

and

$$\frac{4\ Q}{x_{max}{}^{1.911}} = \frac{4\ Q}{(7.5\ H^{1.098})^{1.911}} \qquad \text{(F-48)}$$

$$\overline{\chi}_{max} = \frac{0.085\ Q}{H^{2.1}} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad \text{(F-49)}$$

$$\chi_z = 0.113\chi^{0.911} \qquad \text{(F-50)}$$

$$\sigma_z = 0.113\ (7.5\ H^{1.1})^{0.911} \qquad \text{(F-51)}$$

$$\sigma_z = 0.71\ H \qquad \text{(F-52)}$$

Therefore

$$\overline{\chi}_{max} = \frac{0.085\ Q}{H^{2.1}} \exp\left[-\frac{1}{2}\left(\frac{H}{0.71\ H}\right)^2\right] \qquad \text{(F-53)}$$

$$= \frac{0.085\ Q}{H^{2.1}}\ (0.371) \qquad \text{(F-54)}$$

Therefore:

$$\overline{\chi}_{max} = \frac{3.15 \times 10^{-2}\ Q}{H^{2.1}} \qquad \text{(F-55)}$$

Since the NO_x standard is 1.0×10^{-4} g/m^3, the NO_x severity equation is:

$$S_{NO_x} = \frac{(3.15 \times 10^{-2})\ Q}{1 \times 10^{-4}\ H^{2.1}} \qquad \text{(F-56)}$$

$$S_{NO_x} = \frac{315\ Q}{H^{2.1}} \qquad \text{(F-57)}$$

4. AFFECTED POPULATION CALCULATION

Another form of the plume dispersion equation is needed to calculate the affected population since the population is assumed to be distributed uniformly around the source. If the wind directions are taken to 16 points and it is assumed that the wind directions within each sector are distributed randomly over a period of a month or a season, it can be assumed that the effluent is uniformly distributed in the horizontal within the sector. The appropriate equation for average concentration ($\overline{\chi}$) is then:[40]

$$\overline{\chi} = \frac{2.03\ Q}{\sigma_z u x} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \ (\mathrm{g/m^3}) \qquad \text{(F-58)}$$

To find the distances at which $\overline{\chi}$/AAQS = 0.1, roots are determined for the following equation:

$$0 = \left\{\frac{2.03\ Q}{\mathrm{AAQS}\,\sigma_z u x} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]\right\} - 0.1 \qquad \text{(F-59)}$$

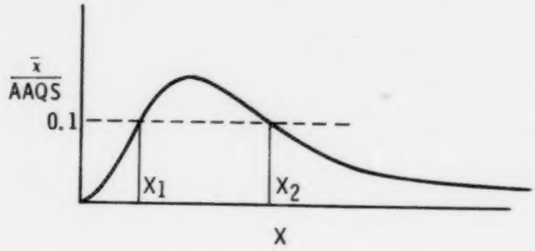
keeping in mind that:

$$\sigma_z = a\ x^{\ b} + c$$

where a, b, and c are functions of atmospheric stability and are assumed to be for stability Class C.

Since equation F-59 is a transcendental equation the roots are found by an iterative technique using the computer.

For a specified emission from a typical source, $\overline{\chi}$/AAQS as a function of distance might look as follows:



The affected population is then in the area

$$A = \pi(X_2^2 - X_1^2) \qquad \text{(F-60)}$$

If the affected population density is D_p then the total affected population P is

$$P = D_pA \text{ (persons)} \qquad \text{(F-61)}$$

SECTION IX

GLOSSARY OF TERMS

ANNEALING - Controlled heating and cooling of glass to remove objectionable stresses.

BATCH - Mixed glass raw materials.

BATCH HOUSE - Structure where raw materials are stored, weighed and mixed.

BOOSTING - Supplemental electrical heating in the glass furnace.

CHECKERS, CHECKERWORK - A network of refractory ducts on both sides of a glass furnace, used as heat exchangers.

CULLET - Scrap glass that is to be recycled.

DEBITEUSE - A rectangular refractory collar with a slot, placed in the melting tank. Sheet glass is drawn through it.

FINING - Process of removing gas bubbles from molten glass.

FLOAT PROCESS - Process for making flat glass by floating molten glass on a bath of molten tin until the glass hardens.

FLUX - Agent which promotes melting by reacting with silica to form lower melting compounds.

LEHR - A long oven for annealing glass continuously.

MELT - The molten glass in the glass furnace.

REFINING - Process of conditioning the molten glass to remove gas bubbles and undissolved grains of sand.

TANK - That part of the glass melting furnace which holds the molten glass, made of refractory material.

REGENERATORS - Chambers of refractory checkerwork on both sides of the melting furnace. Hot exhaust gases from the furnace pass through one regenerator and heat it while combustion air passes through the other regenerator and is heated. At intervals of 20-30 min. the flow is reversed.

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SECTION X

CONVERSION FACTORS[63]

To convert from	to	Multiply by
degree Celsius (°C)	degree Fahrenheit	$t°_F = 1.8\ t°_C + 32$
degree Kelvin (°K)	degree Celsius	$t°_C = t°_K - 273.15$
joule (J)	British thermal unit	9.479×10^{-4}
kilogram (kg)	pound-mass (lb mass) avoirdupois)	2.204
kilogram (kg)	ton (short, 2000 lb mass)	1.102×10^{-3}
kilometer^2 (km^2)	mile^2	2.591
meter (m)	foot	3.281
meter (m)	mile	6.215×10^{-4}
meter^2 (m^2)	foot^2	1.076×10^1
meter^3 (m^3)	foot^3	3.531×10^1
metric ton	pound	2.205×10^3
pascal (Pa)	bar	1.000×10^{-5}
pascal (Pa)	inch of water (60°F)	4.019×10^{-3}
second (s)	minute	1.667×10^{-2}

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[63] Metric Practices Guide. American Society for Testing and and Materials. Philadelphia. ASTM Designation: E380-74. November 1974. 34 p.

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METRIC PREFIXES

Prefix	Symbol	Multiplication factor	Example
giga	G	10^9	5 GJ = 5×10^9 joules
mega	M	10^6	5 MJ = 5×10^6 joules
kilo	k	10^3	5 kg = 5×10^3 grams
milli	m	10^{-3}	5 mb = 5×10^{-3} bar
micro	μ	10^{-6}	5 μm = 5×10^{-6} meter

SECTION XI

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